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# Prosthetic Heart Valve Orifice Area Detection By Using A Combined Shock-Anisotropic Coherence Filter To Improve Level Sets Algorithm

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**Research Article**

**Keywords:** Computer Vision, Artificial Heart Valve, Object Detection, Anisotropic Filter, Shock Filter

**Posted Date:** November 3rd, 2026

**DOI:** https://doi.org/10.21203/rs.3.rs-11590596/v1

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**Additional Declarations:** The authors declare no competing interests.

# Prosthetic Heart Valve Orifice Area Detection By Using A Combined Shock-Anisotropic Coherence Filter To Improve Level Sets Algorithm Results

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**Abstract**

Prosthetic valve is a synthetic or tissue substitute for the natural valve. It is designed to mimic the natural valve's normal opening and clos-ing motions . The need for replacing heart valves increased drastically as the heart valve diseases became one of the dangerous death cause in the world. "Global demand for prosthetic heart valve market expected to reach USD 5,302.1 million in 2021 and growing of 9% from 2016 to 2021". Unfortunately, Biological valves tend to fail over time, requir-ing replacement in 30% of patients within 10 years and 50% within 15 years. The demands for testing prosthetic valves are crucial to main-tain a robustness, durability and compatibility to improve patient health care which insure a place in the global market. This article discuss a novel method for automatic detection of a leaflet edges around ori-fice area opening for PHV (Prosthetic Heart Valve). A pre-processing algorithm using a combination of Anisotropic and Shock filter is proposed to enhance image quality before using a level set to detect PHV edges. This technique shows great capabilities to detect leaflet edges and provide additional enhancement compared to the other works.

**Keywords:** Computer Vision, Artificial Heart Valve, Object Detection, Anisotropic Filter, Shock Filter

# 1 Introduction

The left ventricle heart valve has three leaflets that control opening and closing of the blood flow through the left ventricle. In some cases a calcification causes thickness of those leaflets which may alter the normal opening and closing of the valve. This problem requires replacing the heart valve with another prosthetic one. The prosthetic heart valve (PHV) needs extensive testing before implanting it in the human body. The testing procedure can be done in the lab and a high speed camera can be used to record the valve movements. After that a computer vision algorithm is needed to analyze the image.

Unfortunately, artificial heart valve is prone to failure and has a lifetime which requires rigorous testing and quality assurance before implanting it. Computer vision algorithms are used to enhance and detect leaflet edges, esti-mate orifice area and detect any abnormalities in it. In some cases babies are born with some abnormalities like having less than three leaflets, aortic valve stenosis or dilation in the valve area. These abnormalities cause mismatch and irregular behavior of normal measurements which requires special arrangement and testing for the patients. In some cases an intervention surgery is needed to fix these abnormalities to restore the natural cardiac behavior. Before any intervention a special quality and engineering evaluation is done to estimate the amount of measurement error or mismatch which is the topic of the article.

The contribution of the article summarized as follows:

- Video frame detection and preparation
- Image enhancement
- Edge detection and concavity removal
- Noise removal and leaflet identification
- Final clean valve image generation

The structure of the rest of the article is as follows. Sec 2 chapter back-ground. Sec 3, introduce the research methodology. Sec 4 discusses results. Sec 5 is the discussion . While Sec 6 concludes the article.

# 2 Background and Related Work

There are various methods proposed for PHV leaflet tracking includes digital kymography, thresholding, and deformable models, but the main work that will be considered for comparison [1], [2] used a deformable model. A ground truth image was extracted by using a ground truth tool that designed and imple-mented for this research using Matlab, this tool important for final evaluation to estimate the mismatch and error rate. Fig. 1 shows an example of Aortic valve in opening and closing cycles during normal and stenosis cases.

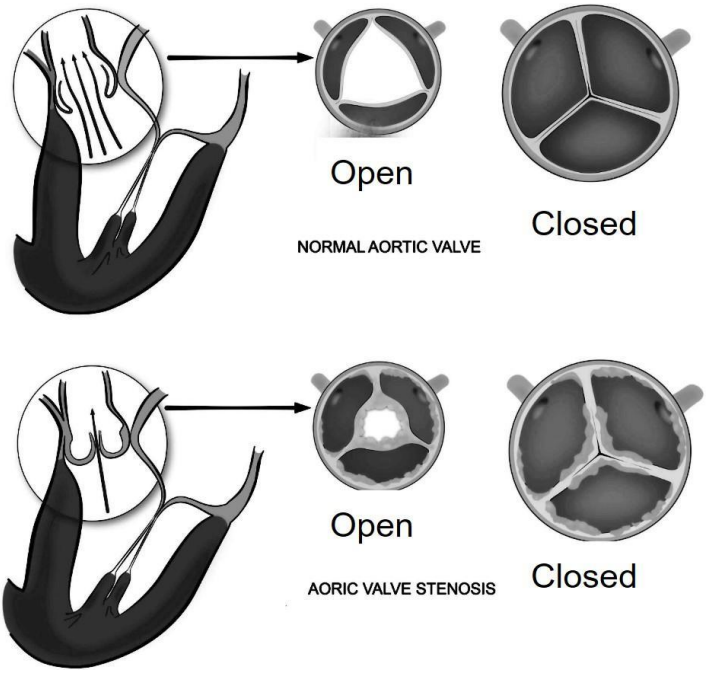



**Fig. 1** Aortic valve demonstration in opening and closing cycle.

The work in [3] proposed a segmentation methodology based on the identi-fying the leaflets edges. Using video frames recorded with a high-speed camera during simulations, an initial estimation of the orifice area is first obtained via active contouring and thresholding after that they are refined to capture the leaflet edges via a curve transformation mechanism. While the research in [4] measure the quality criteria in heart valves. This help in reducing the number of follow-up surgeries to replace worn-up valves by using two methodologies, active contouring and thresholding. In the article [5] they introduce the design of prosthetic heart valves framework. They conduct parametric study to investigate the influence of the geometry on heart valve performance, indicated by the effective orifice area and the coaptation area. The article in [1] implemented a deformable model-based algorithm to analyze orifice area of the prosthetic heart valve images using in vitro simulation.

Where in [6] propose methodology to estimate orifice area of blood flow of the mechanical heart valve. This study aid clinicians in explaining Doppler-derived and catheter-measured pressure discrepancies, validating clin-ical techniques for quantifying effective flow areas, and optimizing valve size for implantation. While valve area and pressure gradient evaluated in [7] using Doppler eco cardiography. The study found peak and mean valve gradient data are less useful because they depend on cardiac output, which increases with body size. The exponential relation between pressure gradient and indexed

prosthetic valve area may allow the formulation of preoperative guidelines to avoid mismatch between prosthesis size and body size.

The study in [8] mentions that (1-2) % of babies were born with a bicuspid valve instead of three leaflets. This case causes either aortic valve stenosis or dilation which requires a surgical intervention.

# 3 Methodologies

The article proposed a method done by designing a combined Shock-Anisotropic Coherence filter to enhance video frames quality before automatic segmenta-tion by Level Sets algorithm. Shock filter has been improved, and different schemes of Anisotropic Filter tested for this purpose, concavity removal algo-rithm applied to remove small concavities attached to the leaflet edges and Canny edge detection method used to detect the final leaflet contour. Fig. 2 represents the article contribution flowchart.

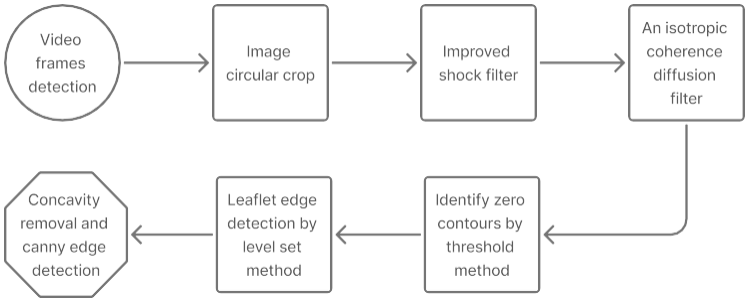



**Fig. 2** Flowchart of the research methodology.

## 3.1 Shock filter

Shock filter is a morphological method, and it "shocks" an image iteratively by dilation and erosion to create ruptures at the edge pixels [9]. This process makes shock filters applied to edge enhancement and segmentation. The algo-rithms are based on Partial Differential Equations (PDE) [10]. Eq. 1 shows the shock filter equation.

$$u_t = sign(delta(u). * \text{gradient(u)}) \quad (1)$$

Where u is the image, and sign function is the Laplacian operator which decides that the pixel should be either dilated or eroded [11]. The gradient is

slope of the edge and useful to detect edges and identify image skeleton. While t is the time for running the instance at the object.

The implementation of Shock filter based on the work done in [12], and I have improved the implementation to use Laplacian of gaussian kernel other than standard gaussian smoothing. This improvement shows a remarkable amount of edge sharpening and background removal other than previous one. Shock parameters set to be as follows, dt=1, mask size set to be 65% of circular cropped image size. Testing shock filters shows that the good results main-tained with mask size between (65-100) % of Cropped image and the mask size should be an even number. Number of iterations set to be 1 as a standard for this algorithm, increasing iterations would increase the ruptures which lead to lose some image details. However, increasing iterations affect the loss of some image data but it may be useful for images that have a high concavity, and its effect can be worse if the image didn't have remarkable concavities. Matlab algorithm set to ensure these conditions. Fig. 3 depicts the difference between standard Shock filter and Improved one, image frame 0291 used for this example.

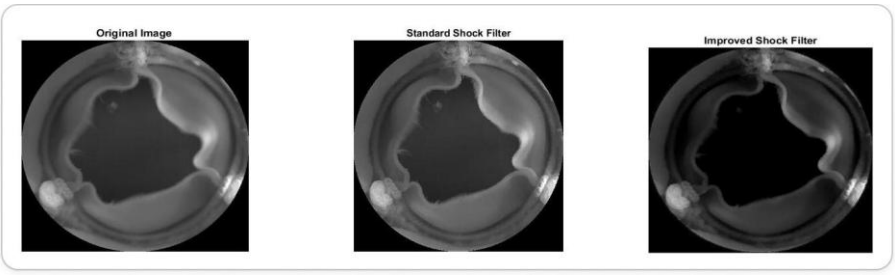



**Fig. 3** Left: Original Image Frame 0291, on the middle: Standard Shock filter, on the right image: Improved Shock filter.

## 3.2 Anisotropic coherence filter

Meaning of Anisotropic explained as An = not; iso = the same; tropic = direction (from Greek tropos "turn"). So, anisotropy means "not the same in all directions". The anisotropic diffusion filtering method consist of two steps. The first is describing the image structure with the commonly used structure tensor also referred to as the" second-moment matrix". The second step is transforming the structure tensor into a diffusion tensor for edge enhancing diffusion filtering [13].

The original shock filter [9] has been developed in 1990, and it can't remove noise. Therefore, an anisotropic diffusion filter [14] has been proposed to remove the noise and enhance edge sharpening. The diffusion can remove not only noise but details of the image [10]. However, some image details can be removed at certain Anisotropic-Coherence filter parameters, this can be good for PHV tracking as it can reduce the effect of PHV fluffs which will improve

the performance of edge tracking by removing the small fluffs and preserving all leaflet details as it not be affected. Fig. 4 shows various schema of anisotropic coherence filtering to the PHV and compares it with shock filter.

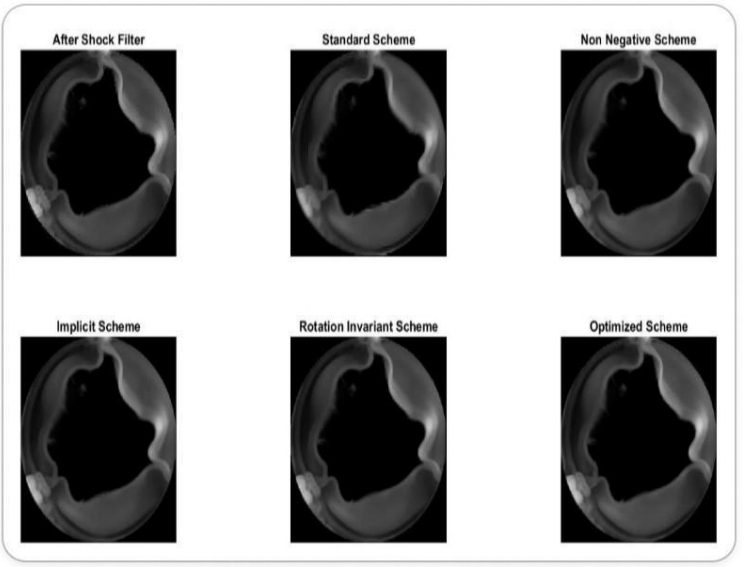



**Fig. 4** Comparison of various anisotropic cohesion filter schema in addition to image filtration by shock filter.

The basis of the method used is the one introduced by Weickert [15]. Eq. 2 is the equation for anisotropic filter.

$$\frac{\partial u}{\partial t} = \nabla.(D\nabla u) \rightarrow uk+1 = \tilde{} uk + (\nabla.(\nabla.(D\nabla u))) \quad (2)$$

Where ∇ is the gradient , D, is the diffusion tensor and u (u(t,x,y,z)) is the image. x,y,z the pixel coordinate and t is the diffusion time [15] , [16].

The method is explained in five steps as follows:

1. Calculate Hessian matrix from every pixel of the Gaussian smoothed input image. It is a square matrix of second-order partial derivatives of a scalar-valued function. It helps to describe the local curvature of a function of many variables.
2. Gaussian Smooth the Hessian, and calculate its eigenvectors and values (Image edges give large eigenvalues, and the eigenvectors corresponding to those eigenvalues describe the direction of the edge).
3. The eigenvectors are used as diffusion tensor directions. The amplitude of the diffusion in those directions are based on the eigen values and determined by Weickerts equation.
4. A Finite Difference scheme is used to do the diffusion.

5. Back to step 1, till a certain diffusion time is reached.

A universal quality index for Anisotropic Filter compared to the improved Shock filter output calculated based on structural similarity index proposed in [17], results shown in Table 1. The results show that an optimized scheme has the best quality enhancement capability based on the universal standards [17].

**Table 1** Quality index of different Anisotropic filter schema

| Quality index/ Anisotropic Scheme | Standard Scheme | Non Negative Scheme | Implicit Scheme | Rotational Invariant Scheme | Optimized Scheme |
|---|---|---|---|---|---|
| Image Quality Index | 62.59% | 76.82% | 76.82% | 84.63% | 86.25 % |

### 3.2.1 (DRLSE) Distance Regularized Level Set Evolution Algorithm

The DRLSE algorithm requires a pre-existing contour to evolve. An initial rough contour must be generated. The DRLSE area term's coefficient controls the expansion or contraction force imposed on the zero-level contour during the evolution. In our case, as the orifice area is much more homogeneous than the rest of the image, it is preferable to have the contour initialized well within the valve orifice and expanded outwards. The initial contour is generated by taking the perimeter of a binary region, slightly morphologically eroded, found via dynamic thresholding [18]. Fig. 5 is the evolution direction of the initial seed contour.




**Fig. 5** Initial Contour for image frame 0291. The blue arrow is the level set evolution direction .

The threshold techniques fail in some cases if we use the original image for this purpose. To enhance thresholding capabilities, a smoothed image by opti-mized Anisotropic-Coherence filter used, this step will enhance thresholding as the blurry noise will be removed, edges smoothed, sharper and orifice area background noise removed. This technique maintains the robustness and sta-bility for initializing the zero contour in a successful way. Fig. 6, depicts the evolved area in gray color inside a filtered image after a combined Improved Shock-Coherence Anisotropic filer has bee applied at different schemes.

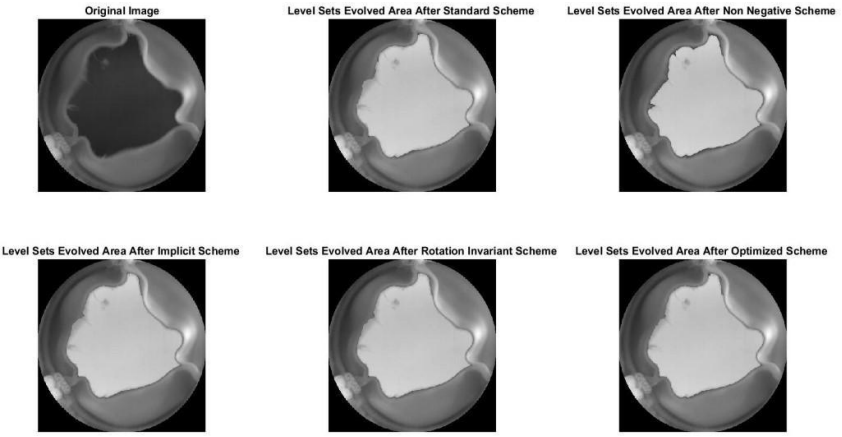



**Fig. 6** Level sets evolved area in gray color inside an original image at different anisotropic schemes at frame 0291.

### 3.2.2 Concavity removal

After orifice area detected by Level-Sets, small concavities attached with PHV can affect the accuracy of leaflet detection. To remedy this issue a dilation-erosion morphology process applied. Dilation with disk size 20 followed by erosion with the same size used to remove the small concavities. Using the same disk size of dilation-erosion guarantee that the original area preserved and not affected. Fig. 7 shows the mechanism effect of concavity removal.

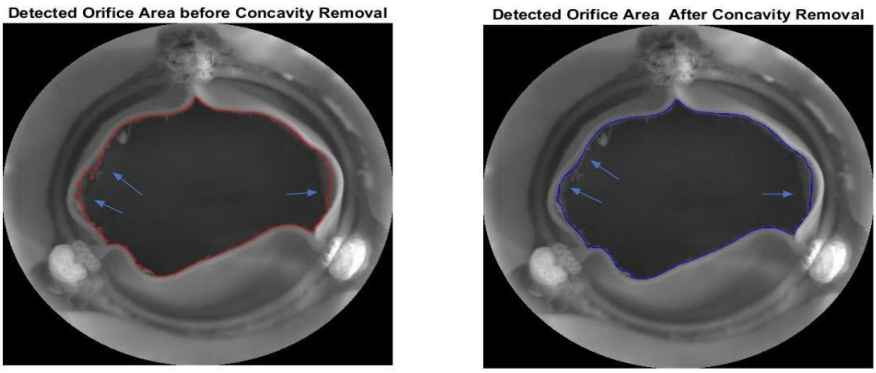



**Fig. 7** On the Left: Detect Edges before Concavity removal. On the Right: Detected edges after concavity removal Frame 1392. Blue arrows denote to the concavity locations.

# 4 Results

## 4.1 Comparison the results with ground truth image:

Ground truth image has been extracted by using image segmentation process. Ground truth images are important as it will be considered as a reference for results comparison. The ground truth image binarized as shown in fig. 8 Different Level Sets outputs resulting from different anisotropic schemes are displayed in colors inside a binarized ground truth image. A small white spot in overlaid images reflects the area that is not matched between ground truth and evolved Level Sets area. By using a visual inspection, it can be concluded that the optimized scheme shows the best output result, which is almost match the whole area with minor errors.

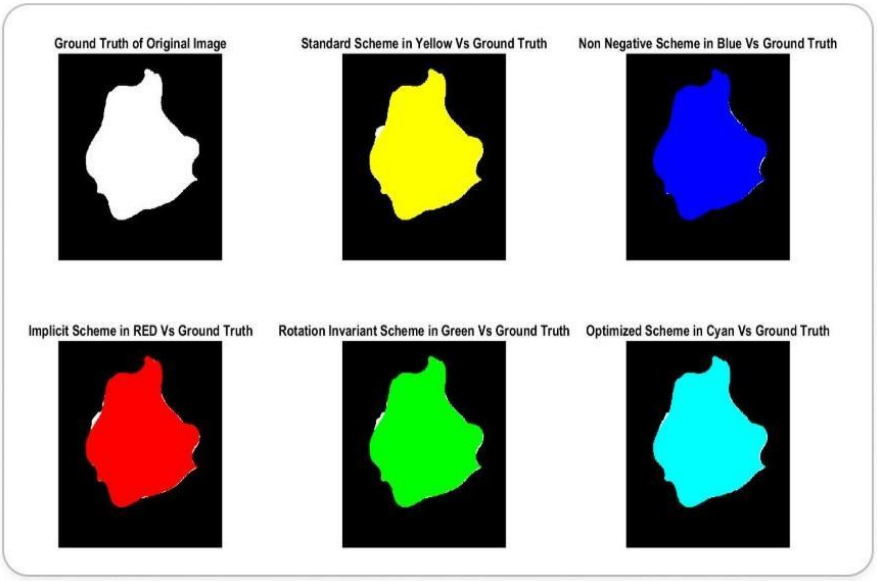



**Fig. 8** Different Anisotropic schemes are displayed in colors inside ground truth which displayed in white image for frame 0291.

## 4.2 Quantitative evaluation:

In this section I will introduce different quantitative evaluations to test the ability of the proposed work to enhance PHV leaflet detection. The evaluation will compare the ability of different anisotropic filters schemes to enhance edge detections and fluffs removal as shown in Table 2. In parallel way an optimized scheme which shows the optimum results will be compared with the mentioned works in [1],[2], [18]. Hausdorff distance has been used as the main criteria for evaluation in the compared work. In addition, I will use the Jaccard Similarity Index as it can give an extra information about the similarity.

Fig. 9 shows Jaccard similarity index and Hausdorff distance. The Haus-dorff Distance is a mathematical construct to measure the ”closeness” of two sets of points that are subsets of a metric space. Such a measure may be used to assign a scalar score to the similarity between two trajectories, data clouds or any sets of points [19]. The Jaccard coefficient measures similarity between finite sample sets, and is defined as the size of the intersection divided by the size of the union of the sample sets [20].

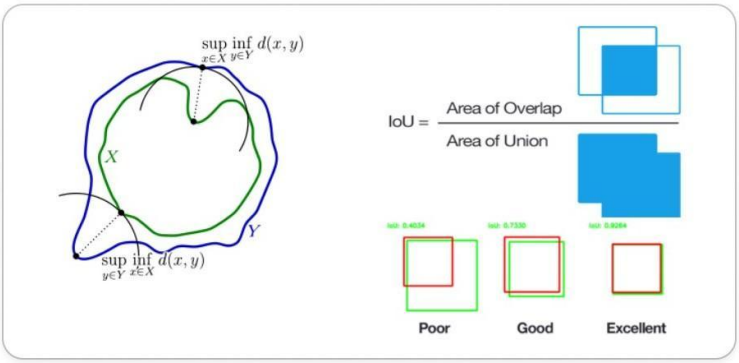



**Fig. 9** Left: Hausdorff Distance. Right: Jaccard similarity index

The data in Table 2, shows the optimized scheme has got the best similarity regarding the Ground Truth based on Hausdorff distance and Jaccard Index which is 4 and 96.91% respectively, this proof that the extracted orifice area almost matched.

**Table 2** Jaccard Index and Hausdorff distances at different anisotropic schema

| **Quality index/ Anisotropic Scheme** | **Standard Scheme** | **Non Negative Scheme** | **Implicit Scheme** | **Rotational Invariant Scheme** | **Optimized Scheme** |
|---|---|---|---|---|---|
| Jaccard Similarity Index | 96.65% | 96.76% | 96.81% | 96.89% | 96.91 % |
| Hausdorff Distance | 4.6904 | 4.3589 | 4.2426 | 4.2426 | 4 |

Table 3, shows Jaccard Index and Hausdorff distances at different frames after optimized scheme compared with ground truth data. While Fig.10 depicts the detect area through different heart cycles.

**Table 3** Jaccard Index and Hausdorff distances at different frames

| **Quality index/ Frame No.** | **0287** | **0291** | **0329** | **0567** | **0578** | **1392** | **1430** |
|---|---|---|---|---|---|---|---|
| Jaccard Similarity Index | 92.28% | 96.95% | 98.61% | 93.39% | 95.73% | 97.53% | 96.59% |
| Hausdorff Distance | 5.0990 | 4.0 | 4.4721 | 3.74 | 4.1231 | 3.4641 | 3.4641 |

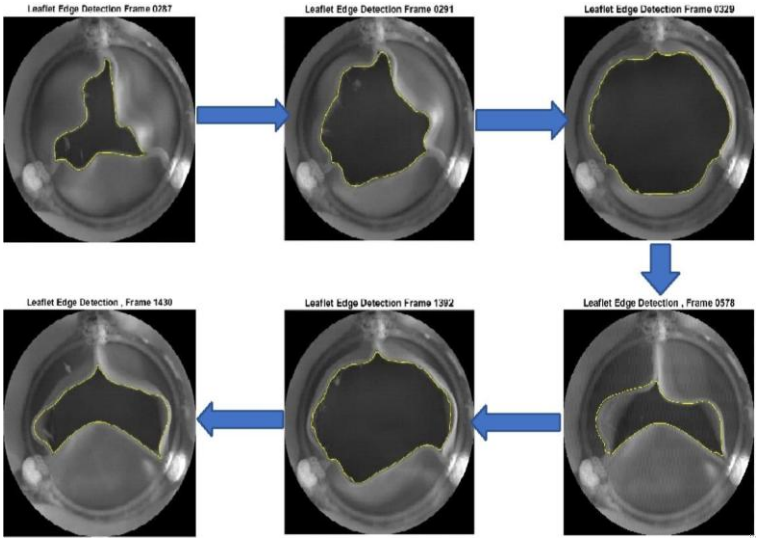



**Fig. 10** Detected area marked in yellow over original Image at different frames from the beginning of the PHV cycle to the end.

Based on the related works mentioned in [1],[2], [18] and to have a fair evaluation I will use the same PHV video frame that used in their evaluation. Hausdorff distance will be considered in this manner as it considered in their work. Table. 4 compare Hausdorff distance number for each method at dif-ferent cases. Proposed method shows an extremely detection improvement as Hausdorff number reduced largely.

**Table 4** Hausdorff Distance of the proposed and compared works

| Method/ Frame No. | 0289 | 0531 | 0567 |
|---|---|---|---|
| Article method | 4.67 | 3.873 | 3.74 |
| Adapted Li et al. | 22.8 | 12.1 | 24.8 |
| Condurache et al. | 16 | 13.2 | 21.8 |
| Burden et al. | 14 | 6.7 | 20.6 |

# 5 Discussion

The article embraced computer vision-based methodology to analyze the pros-thetic heart valve images. The methodology uses a combination of shock filter and anisotropic filter with different schema. The optimized scheme got the best results and shock filters were able to enhance the image contrast. After that, a distant regularized level-set algorithm is used to adapt the initial contour to the grown region. Results show improvements in Hausdorff distance and Jaccard similarity index.

The article methodology succeeded in leaflet edge detection, but some small errors resulted from an internal leaflet area and large fluffs. To enhance the detection sensitivity, different algorithms explored and showed some promis-ing capabilities for Leaflet edge detection. Some algorithms such as, optical flow, edge detection by fuzzy logic, distant transform and seed region growing. Initializing the zero contour should be improved as the thresholding method is susceptible to failure in detection of the initial contour for the closed cycle or partially closed one. Furthermore, future work should focus on algorithm global-ization. Artificial Intelligence may be used to adapt the algorithm coefficients to a huge sample of video frames from different vendors. Artificial intelligence should be used also for training the algorithm how to differentiate between leaflet inner and external area.

# 6 Conclusions

To summarize, this article proposed a novel method to detect PHV Leaflet edges. An improved shock filter has been proposed by using Laplacian of gaussian kernels other than traditional gaussian kernels and shows an improved capability towards fluffs and background removal. Besides, to ensure further improvements to the Anisotropic-Coherence filter used to enhance edge sharpening and noise removal, different schemes have been tested and the optimized schemes show the best results. DRLSE algorithm succeeds in detecting orifice area opening by using evolved area after an initial contour has been initialized. A concavity removal applied to the evolved area by a dilation-erosion morpho-logical process to remove small concavities attached to leaflet edges. The final Leaflet edge has been detected by Canny edge detection. The results com-pared with other works by using Hausdorff Distance and shows an improvement range between 42% to 84.5% in some image frames which prove that the proposed method successful and the results almost match the ground truth data as concluded from Hausdorff distance.

**Declaration.**

**Funding.** Not applicable.

**Conflicts of interest.** The authors declare no conflict of interest.

**Data Availability.** Not applicable. **Code**

**Availability.** Not Applicable.

**Acknowledgment.** Not applicable.

**Competing Interests.** The Authors declare no Competing Financial or Non-Financial Interests.

**Author Contributions.** Conceptualization, K.A.-h.; methodology, K.A.-h.; software, K.A.-h.; validation, K.A.-h.; formal analysis, K.A.-h.; investiga-tion, K.A.-h.; data analysis, K.A.-h.; original draft preparation, K.A.-h; review and editing, K.A.-h.; visualization, K.A.-h.;

**Abbreviations.** The following abbreviations are used in this manuscript: PHV:

Prosthetic Heart Valve.

PDE: Partial Differential Equations.

# Appendix A

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