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Resolution consideration in spatially variant sensors

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Received 19 December 1995; revised 6 May 1997; accepted 22 May 1997

Abstract

Log polar transformations for space variant systems have been proposed and used in active vision research. The idea is to generate an image with a varying resolution over a wide angle field of view. The fovea is of high resolution and the periphery is of exponentially reduced resolution. The justifications for such a sensor are: (i) it provides high resolution and a wide viewing angle; (ii) feature invariance in the fovea simplifies foveation; (iii) it allows multi-resolution analysis; and (iv) it is cheaper and more efficient to build a variable resolution sensor over a particular field of view rather than a uniform high resolution sensor. The receptor density of the human retina is very high, i.e. of the order of $10^8$ receptors at the fovea. The question is, what resolution should space variant active vision systems have? Real visual sensors have been implemented but is the resolution produced high enough? This paper investigates the resolution requirements of a space variant sensor by simulation for a tracking system using raytracing. © 1997 Elsevier Science B.V.

Keywords: Space variant active vision; Complex log mapping; Tracking; Raytracing

1. Introduction

There is a demand for high performance vision systems. New methods are continually being developed to solve more complicated vision tasks. We have also experienced a change of paradigm from passive vision to active vision. Recently, the use of space variant vision systems has been given much more attention following the research into the physiology of the human visual system. The human retina does not have uniform high resolution but has high resolution at the fovea and exponentially decreasing resolution towards its periphery. In addition, the human eyes cover a field of view of about 220° horizontally and about 90° vertically (limited by the shape of the face). This shows that the human visual system has the ability to process multi-resolution images for a wide angle field of view. Following that, variable resolution and wide angle field of view vision systems have been proposed and implemented. One of the possible transformations of a space variant sensor is complex logarithm mapping (CLM). CLM has been proposed, discussed and used in space variant active vision systems [1,2]. This type of CLM space structure: (i) is effective for data reduction, i.e. the amount of information processed in a space variant image is reduced significantly compared to a space invariant image; (ii) is able to provide a wide viewing angle; (iii) allows multi-resolution analysis; and (iv) gives feature invariance at the fovea.

2. Motivation

The use of a log polar sensor for a space variant vision system originated from the fact that the transformation of the retinal image onto its cortical projection can be described as points in log polar space mapped onto cartesian space [3,4]. Note that the validity of this model of the human visual system is the subject of some debate [5-13]. In solving a vision task such as object tracking and object recognition, the vision system is required to process and analyse multiple images. Multiple images are grabbed by guiding the camera towards regions of interest. The small field of view, high resolution fovea is used to extract necessary information to solve the vision task. The process of locating this high resolution portion of the image over regions of interest is termed foveation. On the other hand, the wide field of view provided by the periphery aims to detect motion and guide the camera where to foveate next. Furthermore, images produced by space variant sensors allow multi-resolution analysis. This is important for a number of applications such as foveation and object recognition. For example, two processes are required in a feature recognition system, first the feature detection process will analyse
Recently, it has been used for active vergence control and arbitrarily scaled and rotated 2D shapes, to track a moving target. The space variant sensors have been used to recognize arbitrary patterns in the form of Eqs. (1) and (2).

\[ r = \ln \sqrt{x^2 + y^2} \]  
\[ \theta = \tan^{-1} \frac{y}{x} \]

The space variant sensors have been used to recognize arbitrarily scaled and rotated 2D shapes, to track a moving target and to evaluate the time to impact using optical flow [19,3]. Recently, it has been used for active vergence control and the estimation of time to impact in robot navigation using optical flow [20]. Schwartz introduced a small real constant \( \alpha \) into the log polar map and hence used the log polar mapping of the form \( \ln (r + \alpha) \) [15,16]. This reduced the resolution at the fovea. The sensors have been used for license plate reading using a connectivity graph [15,21].

In both types of log polar forms, a real sensor is used to approximate the architecture of the eye and the use of the CLM to approximate the retinal resolution (photoreceptor density). It is claimed that a visual sensor implemented based on the addition of a small real constant \( \alpha \) is able to remove the singularity problem (i.e. infinite resolution) at the fovea, but introduces a discontinuity problem which makes image processing tasks such as convolution difficult [15,16].

4. Resolution consideration of the log polar map

Existing space variant log polar sensors have a smallest pixel size of \( 10-30 \mu m \) at the fovea [3,16,15]. These sensors have been designed to increase vision system efficiency in that it reduces the amount of information to process compared to a uniform resolution sensor. An example taken from Ref. [16] shows that, when the fovea resolution is doubled, the number of pixels in the log polar sensor increases by 21% compared to an increase of 300% for a uniform resolution sensor. This shows a great reduction in pixel count. As a result, CLM has been proposed for data compression [22-24].

By simulation, we have decreased this pixel size and hence have increased the resolution of the log polar map to match the human fovea. The aim of our simulation is slightly different from that mentioned above in that we aim to achieve higher resolutions possibly up to human foveal resolution. In this way, we will be able to investigate the characteristics of the log polar map and get some idea of what high resolution can achieve. For example, the feature invariance of the log polar map may only be achievable when the foveal resolution is high enough.

4.1. Distance between concentric rings of a log polar sensor

Fig. 1(a) shows the log polar map divided into strips one pixel wide. The one pixel wide log map of Fig. 1(a) is obtained using Eq. (3):

\[ \ln \frac{N}{\text{scale}} \]

where \( n = 1...N \), \( N \) is the width of the image and scale (in pixels) is to produce the required image size given by:

\[ \text{scale} = \frac{N}{\ln \sqrt{(w/2)^2 + (h/2)^2}} \]

where \( w \) is the width of the image and \( h \) is the height of the image. The denominator is the diagonal distance from the
centre to one corner of the image and this distance is divided into a number of pixels after log mapping.

The corresponding cartesian space mapping of Fig. 1(a) shown in Fig. 1(b) is computed using the equation

\[ r = \exp(n/scale) \]

Each segment one pixel wide in log polar space (Fig. 1(a)) is mapped to a concentric ring in cartesian space (Fig. 1(b)). The distance between concentric rings \( D \) in cartesian space (Fig. 1(b)) is given by:

\[ D_i = \exp\left(\frac{n_i}{scale}\right) - \exp\left(\frac{N_i\text{-}1}{scale}\right) \]

where \( n_i \) is the boundary of a one pixel wide segment in the log polar map and \( i = 2...N \). For example, the third concentric ring (shaded) in cartesian space of Fig. 1(b) corresponds to the third column (shaded) of the log polar map of Fig. 1(a).

4.2. Achieving the resolution required by simulation

The change of resolution across the visual field of a log polar sensor is determined by the following.

1. The size of the pixels in each concentric ring in cartesian space. This pixel size is computed from the log polar map.
2. The image size.
3. The field of view of the sensor.

In our simulation, the innermost ring of the log polar sensor is assumed to contain the smallest pixel of the sensor. Three sensors have been simulated to investigate the required resolution for a space variant active vision system to be used in a single object tracking system.

1. Sensor 1 with viewing angle 64°.
2. Sensor 2 with viewing angle 45°.

The difference in viewing angle is because the number of pixels in log polar space is held constant at 360 \( \times \) 360.

In the cartesian space of Fig. 1(b), the density of the receptors in a concentric ring is dependent on the area of the ring. The smaller the distance between neighbouring concentric rings \( D \), the smaller the area between rings, the higher the density of the receptors between rings, and hence the higher the resolution of this concentric ring \( D \).

4.3. Resolution of a log polar sensor

The camera field of view is varied to simulate the desired resolution while the image size is kept constant. Fig. 3 shows the resolution of the three sensors of Fig. 2. Resolution is defined as the ratio of (area in \( \text{mm}^2 \))/(area in pixels) where pixels is an area value. Thus, resolution is computed as:

\[ \text{resolution} = \frac{1}{\pi \times \left(\exp\left(\frac{n_i}{scale}\right)^2 - \exp\left(\frac{N_i\text{-}1}{scale}\right)^2\right)} \]  (4)

where \( i = 2...N \).

The resolution of the three sensors are: 3.1 \( \times \) 10^3 \( \text{mm}^2 \)/pixel, 1.3 \( \times \) 10^3 \( \text{mm}^2 \)/pixel and 4.6 \( \times \) 10^3 \( \text{mm}^2 \)/pixel. Note that the resolution of sensor 1 matches the real log polar sensors implemented with current hardware technology [15,4,16], with sensor 1 having a wider field of view than the real log polar sensor.

Table 1 shows the foveal resolution for the three simulated log polar sensors. The foveal resolutions of sensors 2 and 3 are higher than sensor 1. The ratio of sensor 3 to sensor 2 is approximately 3:1 whereas the ratio of sensor to sensor 1 is 10:1.
2 to sensor 1 is approximately 4:1 so we are approximately quadrupling resolution with each sensor. Do we need such a high resolution fovea? From the experiments we have performed [18,14], the high resolution fovea is required to simplify foveation, i.e. feature invariance can only be achieved at the high resolution fovea. That is, irrespective of the feature type, horizontal lines will result in log polar space. This invariant portion of the image enables us to use a general method to achieve high accuracy foveation points for different types of features.

4.4. Effect of resolution

The next question is, what resolution is really necessary? The top row of Fig. 4 shows edge images where the foveation point is on the boundary of an ellipse in cartesian space. The bottom row shows the corresponding log polar maps of the top row for sensor 1, sensor 2, and sensor 3 respectively. Ideally when foveating on the edge of an object, the resulting two lines ($\phi$) should be 180° apart at the fovea. However, this requires infinite (very high) resolution. Consider Fig. 4(c). The segment near/at ’$+$’ (foveation point) will increasingly appear to be a horizontal straight line in log polar space with $\theta_1 = 90^\circ$ and $\theta_2 = 270^\circ$ if the resolution is high enough. As the resolution decreases, this segment will appear curved and the values of $\phi$ increases, $\theta_1$ decreases and $\theta_2$ increases. This is reflected in the log polar plots shown in Fig. 4(d), 4(e) and 4(f).

Table 3 shows the $\phi$ values for different sensor resolutions and the extent of the horizontal straight lines in log polar space produced because of quantisation. The approximate straight lines at correct foveation allows us to use error measures between a model based on two straight lines an angle ($\phi$) apart. Correct foveation and the resultant value of $\phi$ are obtained by minimising the line fitting error. This relies on feature invariance which is quantitatively indicated in Table 3 by the extent of the straight line at the fovea (given perfect conditions). The template used to measure the error has a window 25 pixels long (the size of the fovea). Hence, from Table 3, it can be seen that the higher the resolution the more the extent of the lines matches the template size. The question that needs to be answered is, how low can the resolution be such that this foveation method can be used in some task such as tracking?

5. The tracking system

The application we consider is proximity tracking [14] which is concerned with tracking the closest object. Initially, to bootstrap, the moving object is detected by computing the difference between two images of the scene at different times. Then the camera is moved to foveate on the moving object. As the object moves, the camera position is updated to keep foveating on the closest interesting feature. The interesting feature is obtained by detecting extremal points (minima/maxima points) in log polar space using an open loop stage for rough foveation (without feedback information) which is followed by the closed loop stage for accurate foveation (with feedback information) [18]. In proximity tracking, only one iteration of the closed loop stage is used for each new image, hence the camera is roughly foveated on the tracked object. Note that rough
foveation will not have an error of more than 1.03 pixels away from accurate foveation. Full closed loop foveation is not used because it requires 13 iterations on average to be completed. Hence, it is time consuming. In a tracking system, it is more important to keep track an object by correcting positional error than to spend time correcting foveation error.

The process of tracking is illustrated in Fig. 5. Fig. 5(a) shows the cartesian scene for a ball being tracked and Fig. 5(b) is the log polar plot of Fig. 5(a). Since the ball is close enough (the feature cut the theta axis) to the camera, no camera pan and tilt is performed. For the next frame, the ball has travelled a certain amount as shown in Fig. 5(c). The amount of error in foveation corresponds to the amount travelled by the ball as indicated in Fig. 5(c) and hence camera pan and tilt are required in order to track the ball using one iteration of the closed loop stage. Fig. 5(d) shows the log polar image after closed loop tracking.

5.1. Experiments

A number of experiments have been carried out to track a ball in a living room scene using sensors 1–3. Fig. 6 shows the trajectory of the ball moving in the living room. It can be seen that, at some stages, the ball passes in front of the fire place or behind the furniture. It also changes its direction of movement in frame 90.

5.2. Description of experiments

For each sensor, three sets of similar experiments were performed in a complex scene with a ball moving in a fixed trajectory.

1. The first experiment is a tracking system executed in a noise free environment.
2. The second experiment performs tracking in an environment with added Gaussian noise.
3. The third experiment performs tracking in an environment with added texture.

For the three experiments, a sequence of frames generated by each sensor is shown after a discussion on the bootstrap condition. The following description is applied to this sequence of frames (see Figs. 8, 10, 13, 16, 18, 20, 23, 25, 26 and 28). Each frame is represented by three images and indicated by the frame number. The first image in each frame indicates the living room in cartesian space after tracking. The foveation point is indicated by a ‘+’ in all the cartesian space images. The middle frame indicates object motion before closed loop tracking in log polar space. The third image shows the ball after tracking using one iteration of the closed loop stage in log polar space. Since no smooth pursuit is performed, most of the pairs of lines in the third image (after tracking) have a small foveation error. This is apparent as accurate foveation will result in two horizontal lines at the fovea, as mentioned before, which is a form of feature invariance. A discussion on the results for each experiment follows the results of the tracking system.

5.3. Tracking with sensor 1

Three experiments are reported using sensor 1 to investigate the practicability of this sensor in term of resolution.

5.3.1. Normal track

The first experiment, set up in a noise free environment, aims to look at the smoothness of the trajectory travelled by an object using sensor 1. Initially, the camera is foveating on an arbitrary point in the living room scene as shown in Fig. 7(a) (note, the whole 3D environment has not been generated, only that needed for the experiments). Fig. 7(c) is the log polar plot of Fig. 7(a). Fig. 7(b) shows the bootstrap condition where the camera is foveated on the ball in cartesian space. Fig. 7(d) is the log polar plot of Fig. 7(b).
Fig. 7. Camera starting position: (a) in cartesian space, (c) in log polar space. Bootstrap condition: (b) in cartesian space, (d) in log polar space.

Fig. 8 shows a number of images for normal track using sensor 1.

5.3.2. Addition of Gaussian noise
To test the robustness of the tracking algorithm, Gaussian noise of $\sigma = 5$ is added to the log polar image of Fig. 7. This simulates error in measurement of the pixel value. Fig. 9 shows the bootstrap condition while Fig. 10 shows some images of tracking using sensor 1 with Gaussian noise of $\sigma = 5$.

5.3.3. Addition of texture
A similar scene to that shown in Fig. 7 is used, but texture is added to simulate a more realistic scene. The textures used are shown in Fig. 11(a)–11(c).

Fig. 12(a) and 12(c) show the camera starting position in cartesian space and log polar space respectively. Fig. 12(b) and 12(d) show the ball after being tracked during the bootstrap condition in cartesian space and log polar space respectively. Fig. 13 shows a number of images for tracking using sensor 1 with texture.

5.3.4. Discussion
Fig. 14(a)–14(c) show the trajectories used by the system in tracking the ball, and the ground truth trajectory of the
ball for the three sets of experiments (normal track, tracking with added Gaussian noise of $\sigma = 5$ and tracking with texture respectively using sensor 1). From Fig. 14(a), it can be seen that the ball is successfully tracked. Note that the ground truth trajectory of the ball is based on the centre of the ball (while we are tracking the edge of the ball). The point to track is changing, for example, when the ball changes its direction of movement at frame 90, the tracking system tracks a different boundary point (this is simply a translation along the $\theta$ axis in log polar space).

Fig. 14(b) and 14(c) show the trajectories when Gaussian noise and texture are added to the system. The tracking system begins to deviate from the true trajectory at frame 45. Further deviation leads to the system failing to track the ball. The tracking system unsuccessfully tracks the ball using sensor 1 because:

- the amount of information that can be extracted is not enough to track the ball,
- other features come into play, i.e. the fire place in the living room confuses the tracking system for tracking with both added Gaussian noise and texture;
- Gaussian noise and texture added to the second and third experiments corrupt the edges of the ball which causes the tracking system to fail.

5.4. Tracking with sensor 2

The same sets of experiments are performed with sensor 2.

5.4.1. Normal track

The first experiment for sensor 2 is tracking in a noise free environment. Fig. 15 shows the camera bootstrapping condition and Fig. 16 shows a number of images during tracking.

5.4.2. Addition of Gaussian noise

Sensor 2 is then tested in the second environment setting (added Gaussian noise of $\sigma = 5$). Fig. 17 shows the bootstrap condition while Fig. 18 shows some images during tracking.

5.4.3. Addition of texture

The third environment setting of added texture to the scene of tracking using sensor 2 is shown in Fig. 19 for the bootstrapping condition follow by some images during tracking in Fig. 20.
5.4.4. Discussion

Tracking with sensor 2 produces good results for the three experiments carried out. The tracking system has been tested and successfully tracks an object for the following situations:

1. when the moving ball occludes other features such as the fire place;
2. when the moving ball suddenly changes its direction of motion;
3. when the moving ball is partially occluded by other features such as the furniture.

The ball trajectories for the three settings compared with the ground truth are shown in Fig. 21. From these trajectories, although the tracking system follows a different path, it can be seen that foveation error in all three experiments is small, as the tracked trajectory does not deviate much from the ground truth value. It can also be seen that more error occurs when the object occludes other objects such as the fire place as the tracking system gets confused (does not know which object is the ball as there is no recognition or predictive tracking being used).
5.5. Tracking with sensor 3

Sensor 3 is of the highest resolution among the three sensors simulated and hence contains more information. The resolution ratio of sensor 3 to sensor 2 is approximately 3.5:1 at the fovea.

5.5.1. Normal track

By repeating the three experiments, Fig. 22 shows the bootstrap condition while Fig. 23 shows some images obtained during the tracking process.

<table>
<thead>
<tr>
<th>Frame Number</th>
<th>Cartesian Space Before Tracking</th>
<th>Log Polar Space Before Tracking</th>
<th>Cartesian Space After Tracking</th>
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</tbody>
</table>

Fig. 20. Tracking using sensor 2 with added texture.

5.5.2. Addition of Gaussian noise

Tracking with added Gaussian noise of $\sigma = 5$ for sensor 3 is shown in Fig. 24 for the bootstrap condition and some images during tracking are shown in Fig. 25.

The success in tracking using sensor 3 lead to Gaussian noise of $\sigma = 10$ added, as shown in Fig. 26 for a number of images obtained during the tracking process.

5.5.3. Addition of texture

Tracking with added texture for sensor 3 is shown in Fig. 27 for the bootstrap condition and a number of images are shown in Fig. 28.

5.5.4. Discussion

Tracking with sensor 3 produces good results for the three experiments. As for sensor 2, tracking with sensor 3 has been tested and successfully tracks an object for the following situations:

1. when the moving ball occludes other features such as the fire place;
2. when the moving ball changes its direction of motion;
3. when the moving ball is partially occluded by other features such as from frame 135 onwards.

The increase in resolution from sensor 2 to sensor 3 has lead to more success in tracking with added Gaussian noise.

Fig. 21. Tracking trajectories with sensor 2 for (a) normal track, (b) tracking with Gaussian noise of $\sigma = 5$, and (c) tracking with texture.

Fig. 22. Camera starting position: (a) in cartesian space, (c) in log polar space. Bootstrap condition: (b) in cartesian space, (d) in log polar space.
By using sensor 3, the tracking system is able to handle Gaussian noise of $\sigma \leq 10$ as opposed to Gaussian noise of $\sigma \leq 5$ for sensor 2.

The ball trajectories for the three settings have been plotted against the ground truth value in Fig. 29. It can be seen from the four trajectories that errors in tracking are small and only apparent during the tracking process when the ball changes its direction and when the ball occludes other features.

5.6. Overall discussion

Table 4 shows the summary of results using sensors 1, 2, and 3 to track a moving ball in a living room scene. From this table, it can be seen that tracking with sensor 1 is not robust enough as it could not handle noise in the environment. As in real time processing, it is impossible to not have noise. We conclude that to track an object requires a resolution that is higher than that of sensor 1, i.e. the current existing log polar sensor. In addition, as the resolution of the log polar sensor increases, the error produced in tracking
decreases. This can be seen from the trajectories in Figs 14, 21, and 29.

Currently, we are able to track the ball for the following situations for sensors 2 and 3.

- Where other features come into play, i.e. the ball occludes other objects.
- When the ball changes its direction.
- When the ball is partially occluded by other objects such as the furniture.

![Fig. 27. Camera starting position: (a) in Cartesian space, (c) in log polar space. Bootstrap condition: (b) in Cartesian space, (d) in log polar space.](image)

![Fig. 28. Tracking using sensor 3 with texture.](image)

<table>
<thead>
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<th>Frame Number</th>
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</table>

![Fig. 29. Tracking trajectories with sensor 3 for (a) normal track, tracking with Gaussian noise of (b) \( \sigma = 5 \), (c) \( \sigma = 10 \), and (d) tracking with texture.](image)

However, the tracking algorithm could not handle the situation when the object is totally occluded; For example, the furniture occluding the ball. Such as after frame 144 for sensor 3. This is why the simulation was stopped at frame 144. However, predicting the direction of the ball using say Kalman filtering [25], as used by others for Cartesian space, may lead to success in tracking the ball.

### 6. Conclusions

We have shown that it is possible to implement a space variant active vision system in log polar space. The advantage of such a system is that we are able to obtain wide angle viewing and high resolution simultaneously which removes the necessity of camera zooming. Wide viewing angle is important for motion detection in the periphery. This enables the establishment of interesting features and hence the camera can be made to foveate on interesting objects.

We have demonstrated that high resolution is important for some application areas such as tracking. With high resolution, the log polar image contains more information which

<table>
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<th>Texture ( \sigma \leq 10 )</th>
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</table>

Table 4

Summary of tracking results using sensors 1, 2 and 3.
can be used to solve a vision task. For example, sensor 3 can handle a higher \( \sigma \) for Gaussian noise than sensor 2 because of the higher resolution of sensor 3 which contains more information than sensor 2. Although the sensors simulated are not practical with the current hardware technology, by simulation we have demonstrated the need for high resolution. Note that there are other applications where a lower resolution is feasible. Also, zooming can be used to achieve resolution at the expense of mechanical complexity and speed. Hopefully, in the future, with advances in hardware technology, the implementation of such a sensor is possible. In addition, this work may serve to encourage others to implement such a high resolution sensor.

In conclusion, we have described the significance of resolution for a space variant sensor to be used in an active vision system. The advantage of wide angle viewing has been emphasized to detect motion in the periphery. The ability to obtain an image that covers the high resolution region and yet provides a wide angle field of view has been shown to be advantageous. This serves as worthwhile research into the implementation of a high performance system where resolution and viewing angle are taken into consideration in implementing a system.

References


