

# Application of machine vision technology to the development of aids for the visually impaired

D. Molloy, T. McGowan, K. Clarke, C. McCorkell and P.F. Whelan  
Vision Systems Group  
School of Electronic Engineering  
Dublin City University  
Dublin, Ireland.

## ABSTRACT

This paper presents an experimental system for the combination of three areas of visual cues to aid recognition. The research is aimed at investigating the possibility of using this combination of information for scene description for the visually impaired. The areas identified as providing suitable visual cues are motion, shape and colour. The combination of these provide a significant amount of information for recognition and description purposes by machine vision equipment and also allow the possibility of giving the user a more complete description of their environment.

Research and development in the application of machine vision technologies to rehabilitative technologies has generally concentrated on utilising a single visual cue. A novel method for the combination of techniques and technologies successful in machine vision is being explored. Work to date has concentrated on the integration of shape recognition, motion tracking, colour extraction, speech synthesis, symbolic programming and auditory imaging of colours.

**Keywords:** Sensory substitution, rehabilitation technologies, shape description, speech synthesis, motion analysis, colour analysis, tonal description.

## 1. INTRODUCTION

The technology for capturing visual images, processing the data, and displaying the data in an enhanced visual image or other modalities (e.g. auditory and/or tactile) has advanced significantly in the last few years. At the same time, the price of the hardware components of such systems has reduced. However there is still a major lack of knowledge of the optimum strategies for displaying the information when the user can dynamically control the processing of the image. There is the need to develop and evaluate systems to assist visually disabled persons to access visual images in real time.

The number of visually disabled persons in the world is likely to double in the next fifteen years and double again in the following fifteen years. Most of this increase is likely to be in the poorer countries. In the richer countries the number of elderly persons is likely to increase, which in turn, is likely to increase the visually disabled population (Gill 1992). This has important implications for Europe (such as funding of health care), since by the year 2020 a quarter of the European population will be older than 60. About 90% of those with visual disabilities in the developed countries have some useful form of vision that can be enhanced with the appropriate low vision aids (Silver 1992). Since 55% of the visually disabled population live alone, there is a need for devices and services which can assist in getting about, access to information, and daily living (Gill 1993). However these basic needs have been largely neglected.

The Royal National Institute for the Blind in the UK (perhaps the single largest body of influence in this area) has targeted the application of vision technologies to rehabilitation technologies as a major research area. (See Kay (1984) for an excellent review of research and development on aids for the visually disabled). Whereas printed media and computer

generated data (text based) has been made available to the visually impaired, the field of spatial perception has not been as quick to develop, although it was one of the first areas to be examined. Success in the area of text availability have been text scanners with Braille or synthesised speech output, Braille data terminals, text enlargers and tactile text readers. Despite these success the displacement of character based systems by graphical user interfaces poses problems for blind users.

When considering an output display medium for a sensory aid there are four main areas of investigation:

- (1) **Vibrotactile:** The fingertip is sensitive to this type of information (e.g. Braille).
- (2) **Eleccutaneous:** Lightweight. low power electrodes electrically stimulate the skin. Cheaper than (1) but now unpopular due to poor control over skin conductivity.
- (3) **Auditory:** Originally considered as a display medium for spatial orientation devices. Became unpopular because of the large variation in output for different environments.
- (4) **Cortical stimulation:** Involves directly placing an image into the visual cortex of the brain. A lot more research needs to be carried out before this approach can be considered practical (Gill 1993).

## 2. MACHINE VISION AND THE VISUALLY IMPAIRED

The basic aim of the research outlined in this paper, is to investigate ways to convert visual information (shape, colour, and motion) into auditory outputs. The objective of this research is to work towards the development of products that could be used to aid the blind and partially sighted. This is a newly developing research area, which falls under the general heading of *Biodynamics*, and has been undertaken by the Vision Systems Group (School of Electronic Engineering) in Dublin City University. The vision group has, in the past, concentrated on the application of intelligent vision systems to industrial problems. It is hoped that the ideas developed in the 'verbalization' of complex industrial scenes can be redefined and applied to sensory substitution systems for the visually impaired. To this end, three project areas have been identified and investigated. These are summarised below:

- **Scene description for the visually impaired:** This project concentrates on describing simple scenes, such as basic shapes, in terms of a user friendly synthesised voice output. This involves the integration of a speech synthesis package and a commercially available machine vision system.
- **Colour description for the visually impaired:** This work aims at describing colour in terms of musical tonal variations. Initially it was intended to used synthesised speech as a means of describing colour scenes, but our initial investigation has found that this approach presented an information overload to the end user.
- **Motion estimation and description for the visually disabled:** The main difficulty with this task is dealing with the large amount of information that need to be processed to make some sense of the visual world. The current focus of this approach is to derive fast, efficient means of transmitting this information from the camera to the computer so that it can be interpreted and translated to synthesised voice output.

It should be emphasised that this work is not intended to offer the possibility of perfect sensory substitution to those who are visually impaired. To do so would be both misleading and unfair. But as system engineers we have taken the approach that many of the techniques we use in the development of industrial vision systems may be of some use in the initial development and promotion of research in this area. This is a first tentative step into a research area prone to the danger of unduly optimistic expectations.

To gain acceptance as a worthwhile aid for the visually impaired a vision system must fulfil many stringent requirements. Cost, ease of use, usefulness and durability are major factors in the design. Close to real time operation is also required. Visual impairment can arise as a result of many causes and is often accompanied by other disabilities also. The nature of the impairment may have great consequences for the vision system options. The task of overcoming such a design problem may be reduced by adopting techniques that have proved successful in the areas of visual inspection. There are however significant differences between a visual inspection system and a vision substitution system;

- A vision substitution system will have to deal with environments outside its control i.e. lighting, movement etc.
- The scenes under consideration will not be known in advance.
- In visual inspection the system is examining a finite set of characteristics.
- The vision substitution system will have to be portable.
- A vision substitution system will have to operate with a high level of user interaction.

### 2.1 The use of sound

The human hearing system is quite capable of processing sound and speech that may be of low quality in a noisy environment. An auditory image mapping system tends to be intrusive on other information processing facilities of the hearing system. It therefore must provide an easy to learn high resolution mapping of the environment under examination that can be used to compensate for its dominance. Despite these restrictions auditory imaging has been used successfully in several personal aids for the visually impaired.

The *Sonicguide* (Kay 1984) provides a binaural display of echoes from multiple objects. Echoes in the field of view produce an almost continuous display of tones. This type of display was judged to be quite complex yet those who persisted in using the device gradually perceived their environment as a complex set of sound patterns from which the necessary information could be decoded.

The mobility sensors above use a form of auditory display. A more complex and up to date use of auditory display is explored in (Meijer 1992). The implementation of a device for transforming a grey level image into an audio spectral image is discussed. A 2-dimensional spatial brightness map of an image is transformed into a 2-dimensional map of oscillation amplitude as a function of frequency and time. Evaluation of the image sound mapping by a reverse transform demonstrated the information preserving properties of the transformation. From the above examples it can be seen that auditory visualisation can result in a high information display rate while still maintaining some similarity with the visual experience. Auditory visualisation would be perhaps best used to complement a conventional speech description.

## **3. SPEECH SYNTHESIS FOR SHAPE DESCRIPTION**

Ideally, a system for describing scenes would take any scene, identify all objects within that scene, identify the interrelationships between the objects, and describe the scene by means of some auditory or tactile method.

There are many problems which may be associated with scene descriptions. For example if you look at objects from different angles then they appear different. Also trying to perceive objects from two dimensional images can be quite difficult. There are other problems such as shadows and geometric distortions due to the camera.

To simplify the scenes only two dimensional scenes will be examined, more specifically overhead views of objects or scenes (e.g. cutlery on a table etc.). To date only one part of this system has been developed and this program is capable of analysing any shape and storing certain characteristics of that shape in a database so if the shape is ever encountered again then the program will recognise it.

### 3.1 Initial Research

Initially when developing a program to recognise specific shapes, several methods of tackling the problem were examined. Template matching was considered but as well as being considerably slow and inefficient it did not account for changes in the size and orientation of the object. radial coding and skeleton matching were examined and it was observed that although they were able to account for changes in orientation they were not able to account for changes in size.

Eventually it was decided to obtain certain characteristics of shapes and use these as a reference when identifying shapes. Characteristics were required which would not change when the size or orientation of the shape changed on the screen. Some of those characteristics chosen are shape factor, the ratio of the maximum and minimum radii from the centroid of the shape, the number of corners, a comparison of sides of equal length and equal angles, symmetry and the number of bays the shape has.

Speech has been chosen as the method to be used for describing scenes for two main reasons. Firstly it is the most popular method of communicating among the visually impaired. This statement is supported by statistics provided which indicate that less than 20% of the visually impaired persons in the United Kingdom are capable of reading Braille (Gill 1993). The second reason for using speech is that good quality speech synthesisers are commercially available at reasonable prices.

Tactile displays and Braille keyboards are available commercially, but only a small percentage of visually impaired persons can afford them and are capable of using them. Of the 991,000 visually disabled persons in the United Kingdom, approximately 19,000 are capable of reading Braille, 13,000 actually do read Braille and only 9,000 can write Braille (Gill 1993). Also an average human can absorb recorded spoken information (e.g. speech synthesiser) at approximately 120 words per minute whereas a typical Braille reader can only read approximately 80 words per minute.

It was decided that the new Speech Manager package which is part of Apples new PlainTalk technologies was to be used to produce the speech. This provided the best possibilities for interfacing with the MacProlog environment on the Apple Macintosh computer. Speech Manager is a new package which is capable of good quality speech and provides several facilities for altering and manipulating speech to suit specific needs.

### 3.2 Design and Implementation

The Vision Systems Group at Dublin City University uses the MacProlog environment on Apple Macintosh computers. Image Inspections intelligent cameras are also used and the image processing commands contained within this camera provided the means to implement the techniques which were mentioned in the previous section. As an experiment this shape program was modified to identify common shapes such as squares, circles, triangles etc.. This was done for two reasons, firstly to test its accuracy and secondly common shapes presented a more difficult task than random shapes.

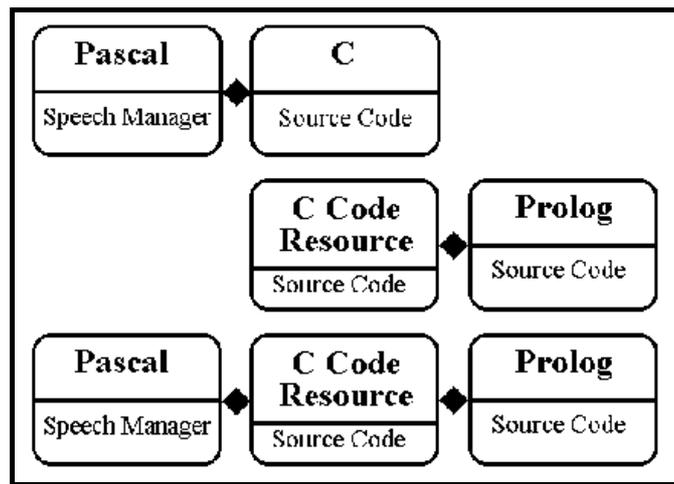


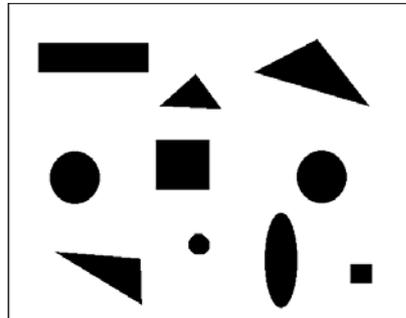
Figure 1. The Application of the C Code Resource

Speech Manager could be interfaced directly with PASCAL and C but not with MacProlog. MacProlog could be interfaced with C using a *C Code Resource*. A *C Code Resource* is a piece of C code which is compiled and linked as a code resource and called from within the MacProlog environment. Therefore a C code resource was written which accessed the Speech Manager package. This code resource was then interfaced with a Prolog program and the resulting system produced successful communication between the Prolog program and the Speech Manager package (McGowan 1994).

Using this interface an entire speech package was developed for the MacProlog environment which is known as MacProlog Text to Speech. This package enables MacProlog users to incorporate speech into the MacProlog software with considerable ease. This package consists of several different voices and the option to change the pitch rate and the

speaking rate. There is also a dictionary and text to phoneme conversion options which enable the user to create more accurate pronunciations.

To demonstrate the work which has been done so far a program was written which combined shape recognition with



There is a rectangle at the top left of the screen.  
There is a triangle at the top right of the screen.  
There is a square at the centre of the screen.  
There is an ellipse at the bottom right of the screen.  
There is a circle at the centre left of the screen.  
There is a circle at the centre right of the screen.  
There is a triangle at the bottom left of the screen.  
There is a triangle at the top centre of the screen.  
There is an unknown shape at the bottom right of the screen.  
There is a circle at the bottom centre of the screen.  
Test complete.

Figure 2. An example output for the Shape description program for the display shown.

speech synthesis. This involved placing several shapes under the camera and by means of speech each shape would be identified along with its location on the screen. The results of one such test are shown below.

#### 4. TONAL DESCRIPTION OF COLOURS

The scene description system under investigation hopes to combine visual information from a combination of sources. This approach will have two major benefits. Firstly, the greater range of visual cues that are covered will go some way in aiding recognition and understanding of scene by the system. Secondly a greater amount of information is available for presentation and description to the user. When a presentation method is faced with the task of describing a large amount of information, a linguistic description via speech synthesis will be severely overloaded. With the above in mind this section of the project hopes to examine a means of providing an alternative colour description system. Specifically it will focus on a system capable of generating a tonal description of colour scenes. Artificial vision systems employed in scene analysis tend to concentrate on providing minimal non redundant images. This processing loses many of the important visual cues. For this reason a straightforward mapping of colour to audio images will be used. The only image analysis techniques to be used are for extracting area information of individual colours.

A link between music and colour has long been debated, somewhat inconclusively. From Pridmore (1992) we learn that the value of exploring such a link is limited and it may be more worthwhile to exploit the similarities of structure between colour and sound. Colour has a cycle of hues while sound has a cycle of tones in an octave. Colours are arranged into levels of saturation while tones are grouped into octaves. Again it is possible to debate the validity of such similarities. An application presented in the paper attempts to provide a visual impression of music to deaf persons. The transformation mapped tone (in any octave) to hue and loudness to brightness. The same tone in different octaves is mapped to different positions in the large display used.

##### 4.1 Colour sensing systems for the visually impaired

All three colour detecting devices for the visually impaired currently available and discussed in Clarke (1994), consider colour as the sole variable under observation. As these systems contend with describing just one area of visual cues a straightforward speech output is used. These devices are limited in their ability to describe the relationships among colours or the form of colours in a scene.

##### 4.2 System outline

Figure 4 illustrates an outline of the colour description system incorporating the Programmable Colour Filter contained within the Intelligent Camera designed by Plummer (1991). Batchelor (1993) provides many explanations and examples of use of this equipment. The use of a high speed look up table enables real time colour segmentation and recognition. If the look up table is suitably programmed an eighteen bit RGB value can be transformed to an eight bit value representing hue and saturation.

As an  $(r,g,b)$  triplet from the RGB channels represent a 3-D vector, the LUT can be seen to represent the unit colour cube. A *colour triangle* is a very useful tool when working with colour systems. The colour triangle has as its vertices the primary colours Red, Green and Blue. The colour triangle, (Figure 3(b)) can be seen as a 2-dimensional slice through both the RGB colour cube, (Figure 3(a)) and the HSI colour space. All levels of hue and saturation are represented in the triangle, while intensity is not.

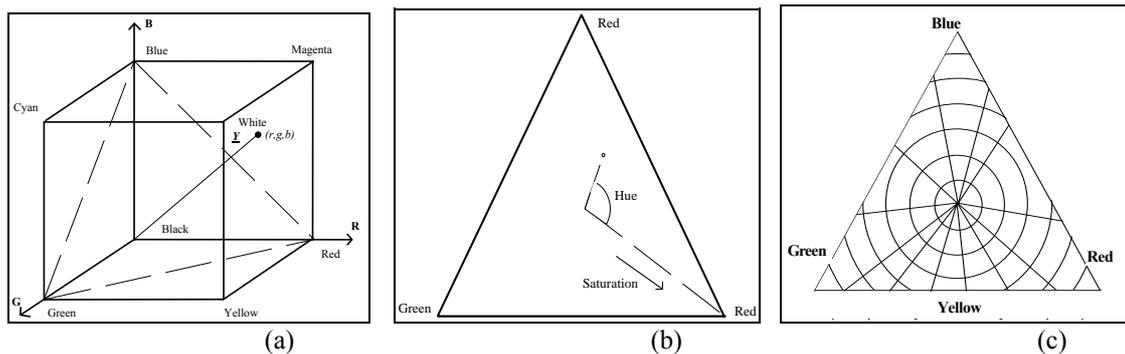


Figure 3.(a) The RGB colour space with an arbitrary colour triplet  $(r,g,b)$ , (b) Section from the RGB cube showing the relationship of HSI parameters to the RGB colour space, (c) showing a filter used in the segmentation of images based on hue and saturation.

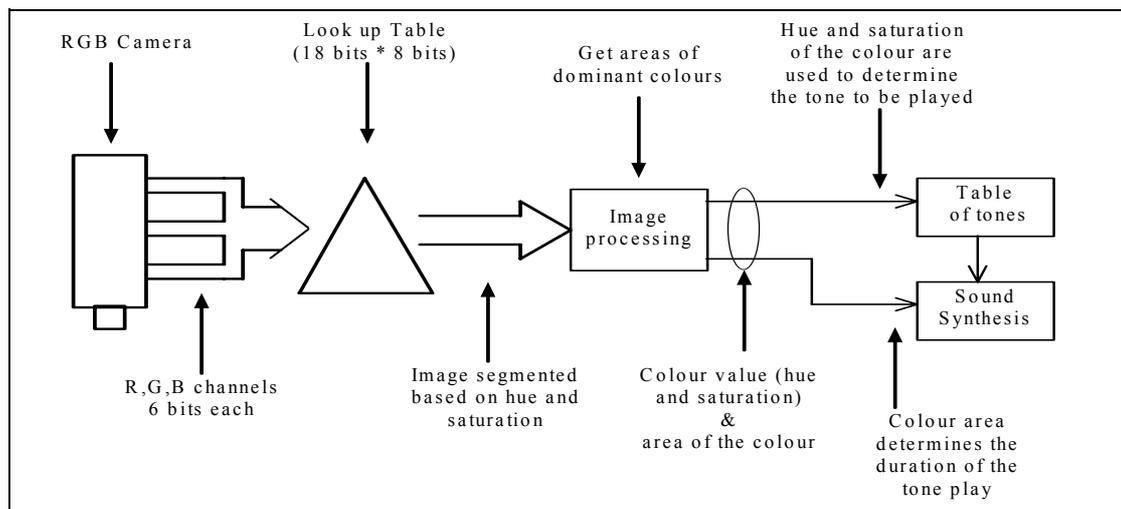


Figure 4. Operation of the Colour to tone converter

For our purposes programming the colour filter consists of generating patterns in the colour triangle that can then be projected throughout the complete LUT. In order to distinguish the hue and saturation of colours a pattern such as that shown in Figure 3(c) is used. The pattern is generated so that each region in the triangle has a distinct intensity. Colours of varying hue and saturation can then be distinguished by thresholding the image that has passed through the PCF. Note that the area allocated to each hue is not constant. This form of colour triangle segmentation was implemented so that in the mapping of hue to single tones the four primary colours, (red, green yellow and blue), are spaced at every third semitone.

#### 4.3 Design description

The sound synthesiser (Macintosh Sound Manager) can play several tones at various levels and frequencies concurrently. For the Current experiments however the four dominant colours in a scene are selected and their corresponding tones played. Considering the effects of processing constraints and the provision a reasonable time for the assimilation of a single auditory image and considering the effects of processing constraints fixed the total display time of a single image to approximately one second. In this short interval the number of colours considered in a scene was restricted to four.

#### 4.4 Results

To fully evaluate the validity of the project it would be necessary to carry out a full range of tests with blind people. Before that we can however evaluate the effectiveness of the transformation at conveying colour information by analysing the audio images and attempting to correlate these with colours. Recording of tones has shown that the auditory images have a rich spectral content over the range 20Hz - 10Khz.

Many people who have heard the application working commented that it was possible to distinguish between various colours. These comments were based on hearing the auditory description of single colours isolated temporally from others. The above spectral analysis results verify the users observations that individual colours can be distinguished. This ability to distinguish individual colours is important as more complex scene descriptions can build up into a complex display. The transformations implemented in this project attempted to match constant colours to constant features in an auditory space. Trials of the system have shown that a means of distinguishing between colours has been provided. It still remains to be examined if the system is successful at providing adequate distinction between multiple colours. The system implemented relied very little on complex image analysis techniques. This minimised the amount of information processing required and provided a more direct image of the scene under view.

## **5. MOTION DESCRIPTION**

A method of motion estimation had to be chosen for this section of the project and after examining the various methods available such as optic flow (Horn 1981, Byrne 1992), feature matching (Roach 1979) and image intensity subtraction, it was decided that the method to be used should have the following features : -

- It should have low computation to operate as fast as possible on the equipment available.
- It should be intelligent so that the motion information could be easily translated into descriptive information.
- It should be implementable on the equipment with which the image processing will be performed.
- It should be interfacable with MacProlog, since this is the environment decided upon to translate the information to the visually impaired and interact between the different description techniques.

Two methods were examined that conformed with these specifications, the methods of centroid tracking and temporal image filtering.

### 5.1 Centroid Tracking

After examining the theory behind the various methods of object tracking it became clear that a real-time method of motion description was required. Optical flow methods and complicated feature matching techniques were found to be too computationally intensive for real-time implementation on the equipment available. The less computationally intensive method of centroid tracking was then examined. This had the following difficulties:

- The background must be captured before the motion sequence begins.
- Objects within the background image cannot move during the motion sequence without severely complicating the motion calculation.
- It is reasonably sensitive to light variations and shadows.

Image A in Figure 5 shows the reference image. This image is usually captured before the motion sequence begins but



Figure 5. Showing the reference image, the image with the object and the extracted results.

could be designed to decide if a large enough light variation had occurred to recapture the reference image. This would recapture the image when no motion had occurred for a certain number of frames. This could be carried out using variable/dynamic thresholding techniques of Prolog+ (Batchelor 1991).

Image B Figure 5 shows a later image from a motion sequence. In this image an object has entered the scene. By image intensity subtraction, thresholding and filtering, image C Figure 5 results. This image then contains the binary region that will be used to perform the centroid tracking algorithm. Figure 6 shows two points that may be extracted from a rigid binary region, no matter what rotation the region has undergone, the centroid and maximum distance from the centroid enclosed by the circumcircle. When there are multiple objects in the scene Prolog is then used to decide the best match between objects in the current and previous scene. It does this by using algorithms based on such information as the area

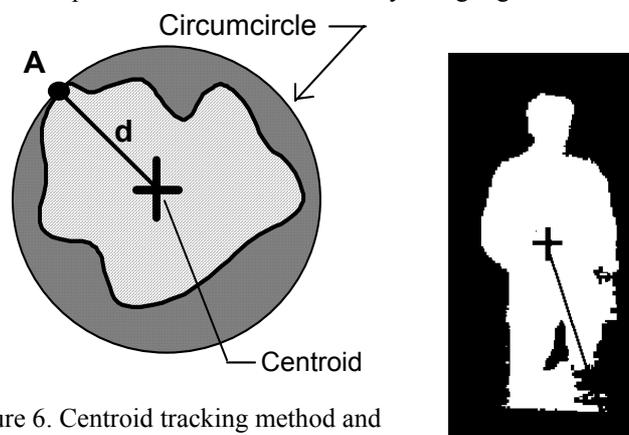


Figure 6. Centroid tracking method and its application to this problem. (Batchelor 1991)

of the region, the velocity of the region and the position of the region. It uses logic and uncertainty weightings to build algorithms to find the best match. This allows objects to be tracked individually in the sequence.

### 5.2 Temporal Image Averaging

Temporal Image Averaging is another fast way of extracting the motion information from the image sequence. It averages the intensities of successive frames according to the formula:

$g(t) = kg(t-1) + (1-k)f(t)$
where $g(t)$ = current "average"
$g(t-1)$ = previous "average"
$f(t)$ = current frame
$0 < k < 1$

When  $k = 0.5$ , the formula then becomes  $g(t) = 0.5g(t-1) + 0.5f(t)$ . This is the same as adding the intensities of the incoming frame to the previous frame and dividing by 2. The result is stored in the previous frame in the next iteration. This method gives a motion "blur" around the object that is moving through the image sequence. When an object stays still over a period of time it will disappear to black on the screen. This method is particularly useful when the background is unknown or changing, since only the motion information in the scene is displayed and there is no need to store a reference image before the motion begins in the sequence. The information is then stored in the same method as before in centroid tracking. Even though the object will disappear into the background when it stays stationary in the sequence, all its information is still available, since if it moves, the moving part reappears onto the screen and only then does a change need to be made in the motion description.

On the equipment available it was only possible to implement with  $k=0.5$ . This is the simplest form of the formula resulting in uniform grey scales on either side of the object. The direction of the object can therefore not be determined. This could be overcome by setting the value to one other than 0.5 resulting in a different shade on the direction that it is travelling. This however was not easily implemented on the equipment available.

5.3 Implementation of a motion tracker

The system of centroid tracking was implemented using Prolog 4.5 on the Apple Macintosh (Molloy 1994). A Think C 5.0 interface was written to perform the serial communication between Prolog and the Intelligent Camera. This allowed

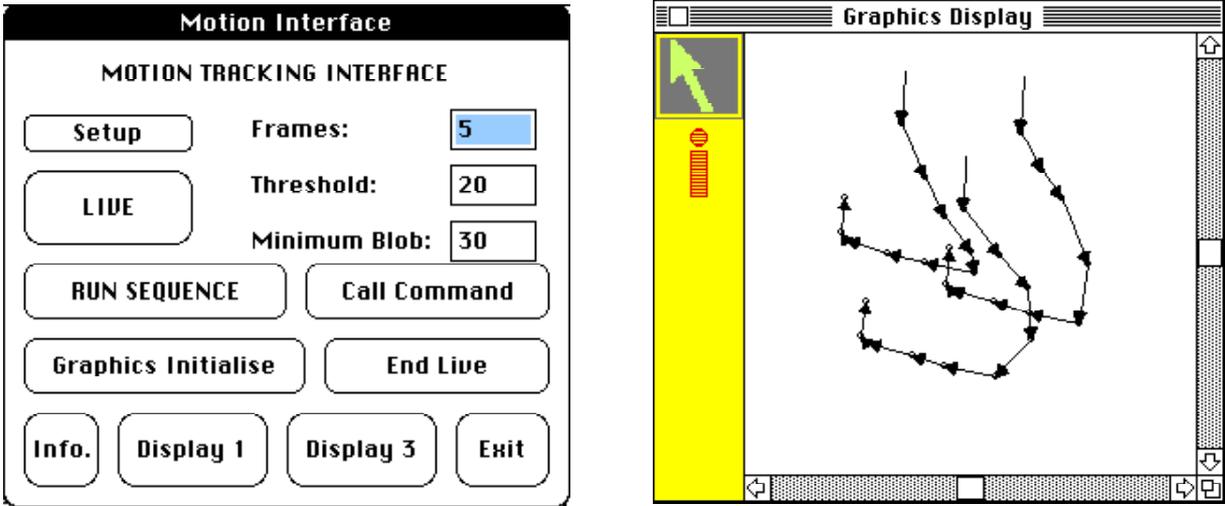


Figure 7. The motion tracker interface and the results display window.

the Intelligent Camera and Prolog to operate in parallel resulting in real world application speed. Figure 7 shows the main interface screen. This was written in Prolog and allows complete control over the motion tracking system. The system operates on the data received from the camera and converts it into the form as shown in the results display. The velocity and direction of each object is calculated through the sequence of images allowing descriptions to be built up - such as the velocity of the object i.e. in the case of human motion this would decide if the human was running or walking. In the case shown in Figure 7 three objects were tracked as they moved down, to the left and then up slightly. These objects were quite close and moving at similar velocities, so the area of the regions played a major part in the motion estimation calculations. This system worked quite well, even on complicated backgrounds provided the camera was stationary and the background known.

The integration of the ideas outlined in Sections 3-5 is not particularly difficult since they are all based on the same system, an intelligent camera linked to the Prolog environment. The combination then involves developing algorithms in the Prolog environment. This could be used, for example, in the case of a person with a red jumper, to track the jumper as a region rather than tracking the entire person as a region. All the information extracted in the three areas can be placed in a database for each object, to allow a more accurate scene description. It also has the advantage that if a speech synthesis package is developed for one section then it may be applied to the other sections without many alterations. One major problem with the combination of the three areas is that of information overload, if all the information available is conveyed to the user. It is therefore more important to convey specific useful information and use the other information in the development of the description algorithms.

## 6. CONCLUSION

Although there are many exciting technological possibilities for visually disabled, there is a general problem in the design of good man-machine interfaces. According to Gill (1993) possibilities for productive research include, telecommunications, satellite navigation, vision substitution systems and the elimination of non-visual display by direct cortical implants (this area of research is still many years away from been of practical benefit).

The work outlined in this communication represents an initial investigation into the application of machine vision techniques and design disciplines to the development of aids for the visually impaired. While the development systems described have indicated the usefulness of the approaches taken, a significant amount of engineering effort would be required to produce a product that is acceptable to the visually impaired community from both a cost and technology basis. Further research must also include the development of a more detailed user requirement specification, the production of prototype systems and the development of training procedures.

It is intended that the sound generation capabilities of the project complement the linguistic description of the scene and motion within the scene. The effects of the combination of these description methods on each other have yet to be fully examined. A possible solution would represent coarse information by a fast straightforward mapping of images to sound effects. A finer description could then carry out a more detailed description and make use of synthesised speech. Some researches in the area of acoustics are proposing that the areas of scientific data visualisation and virtual reality can benefit from the use of complex auditory displays (Kendell 1991). In generating auditory analogues of the visual world there are a great multiplicity and complexity of mappings that can be used to generate auditory displays. By exploiting new techniques in this area it may be possible to provide improved auditory representation of a scene.

## 7. ACKNOWLEDGEMENTS

This research work was supported by seed funding from the National Rehabilitation Board (Ireland). Thanks are also due to Dr. J. Gill of the Royal National Institute for the Blind (UK) for his suggestions and support at an early stage in this project.

## 8. REFERENCES

- B.G. Batchelor (1991), *Intelligent Image Processing in Prolog*, pp49-51.
- B.G. Batchelor (1993), *Interactive Image Processing for Machine Vision*, Springer Verlag, New York, 1993.
- N.Byrne (1992), *Motion Estimation in Computer Vision*, Ph.D. transfer requirement, School of Electronic Engineering, Dublin City University.
- K. Clarke (1994), *Tonal Description of Colours for the Visually Impaired*, B.Eng in Electronic Engineering project report, Dublin City University.

- J. Gill (Ed.) (1992), *Priorities for Technical Research and Development for Visually Disabled Persons*, World Blind Union Research Committee.
- J. Gill (1993), *A Vision of Technological Research for Visually Disabled People*, The Engineering Council.
- B.K.P Horn and B.G.Schunck (1981), "Determining Optical Flow", *Artificial Intelligence*, pp185-203.
- L. Kay (1984), "Electronic aids for blind persons: An interdisciplinary subject", *IEE Proceedings* 131(A-7), pp 559 - 575.
- G. Kendell (1991), "Visualisation by Ear: Auditory Imagery for Scientific Visualisation and Virtual Reality", *Computer Music Journal*, 15(4), pp 70 - 73.
- T.McGowan (1994), *Scene Description for the visually Disabled*, B.Eng. in Electronic Engineering project report, Dublin City University.
- P B. Meijer (1992), "An Experimental System for Auditory Image Representations," *IEEE Transactions on Biomedical Engineering*. 39(2), pp 111 - 121.
- D.Molloy (1994), *Motion Estimation and Description for the Visually Disabled*, B.Eng in Electronic Engineering project report, Dublin City University.
- A.P. Plummer (1991) "Inspecting Coloured Objects Using Grey Scale Vision Systems", Proc. SPIE conf. *Machine Vision Systems Integration*, Boston, MA, Nov. 1990, vol Cr36, 1991, pp 78-92.
- R.W. Pridmore, "Music and Color: Relations in the Psychophysical Perspective," *COLOR Research and Application* 17(1), pp 57 - 61, Feb. 1992.
- J.W.Roache and J.K.Aggarwal (1979), "Computer Tracking of Objects Moving in Space", *IEEE transactions on Pattern Analysis and machine Intelligence* 1,no.2, pp127-135.
- J.H. Silver (1992), "The low vision population", *Priorities for Technical Research and Development for Visually Disabled Persons* - J. Gill (Editor), World Blind Union Research Committee.

D. Molloy, T. McGowan, K. Clarke, C. McCorkell and **P.F. Whelan** (1994), "Application of machine vision technology to the development of aids for the visually impaired", in *Machine Vision Applications, Architectures, and Systems Integration III*, **Photonics East 94**, Proc. SPIE (2347) 31 Oct. - 4 Nov., Boston USA, pp -.