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Improving the Safety and Efficiency of Roadway Maintenance Phase II: Developing a Vision Guidance System for the Robotic Roadway Message Painter

Final Report

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16. Abstract (Limit: 250 words)

Repainting existing roadway markings (turn arrows, STOP messages, railroad crossings, etc.) is an important task for transportation maintenance organizations. MnDOT estimates that over 75% of symbol and message painting is the repainting of existing markings. It would be extremely valuable for an automated painting system to have a vision guidance capability whereby an existing mark could be repainted accurately with little operator input. In this project a vision system was developed that is capable of identifying existing painted pavement markings and determining their dimensions, location, and orientation. Techniques were also developed whereby this information could be used to determine the location of the marking in the workspace of a painting robot to enable it to accurately repaint the marking. The vehicle-mounted robotic painter is still being built and tested, so final test results will not be available until the vision system can be completely integrated with the painter, and the two can be tested together. The accuracy of the projection produced using the techniques developed in this project would suggest that the final system will be capable of repainting pavement markings almost exactly where they appear on the roadway. Expected benefits of the deployment of a vision-guided robotic painting device include improved operator safety, improved productivity, and improved flexibility in roadway marking and repainting operations. Eventual users of a device using this technology could be city, county, state, and federal government agencies and private companies or contractors.

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Technical support and reviews of the project from a user's perspective were also provided by MnDOT personnel.

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Executive Summary

Repainting existing roadway markings (turn arrows, STOP messages, railroad crossings, etc.) is an important maintenance task. Mn/DOT estimates that over 75% of symbol and message painting is the repainting of existing markings. It would be extremely valuable for an automated painting system to have a vision guidance capability whereby an existing mark could be repainted accurately with little operator input. This report describes a project to develop a vision system capable of identifying an existing painted pavement marking and determining its dimensions, location, and orientation. The information from the vision system can then be passed to a robotic painting device (currently under development) to enable it to accurately repaint the marking. This vision system would significantly improve the capability of the device to repaint existing pavement markings.

The work for this project was broken down into functional areas, and each of those areas was further subdivided into specific tasks. First, an image acquisition system was designed, purchased, and installed on a vehicle. Next, software was developed for capturing and processing images, including fisheye lens correction, clipping, and thresholding. Techniques were then developed by which representations of pavement markings could be extracted from the thresholded images, and information on the location and size of the markings could be determined. Finally, this location and size information was used to determine the location of the marking in the workspace of the robotic painting device that is under development.

Over 40 images of pavement markings were collected for test and development purposes. Tests were run to determine the extent of the image processing capabilities and to determine the accuracy with which pavement markings could be automatically identified and located. The system was capable of successfully performing the steps of fisheye correction, clipping, and thresholding on all of the test images. The recognition accuracy was approximately 90%, with unrecognized markings being either very dirty or worn. The ability of the system to translate location information between the image and the robotic painter's workspace was also tested by projecting the geometry of the marking into the image. The resulting projection required only minor manual adjustment prior to being used to determine the location of the mark in the robot workspace.

The vehicle-mounted robotic painter is still being built and tested, so final test results will not be available until the vision system can be completely integrated with the painter and the two can be tested together. The accuracy of the projection produced using the techniques developed in this project would suggest that the final system will be capable of repainting pavement markings almost exactly where they appear on the roadway. Expected benefits of the deployment of a vision-guided robotic painting device include improved operator safety, improved productivity, and improved flexibility in roadway marking and repainting operations. Eventual users of a device using this technology could be city, county, state, and federal government agencies and private companies or contractors.

Chapter 1. Introduction

Repainting existing roadway markings (turn arrows, STOP messages, railroad crossings, etc) is an important task for transportation maintenance organizations. MnDOT estimates that over 75% of symbol and message painting is the repainting of existing markings. It would be extremely valuable for an automated painting system to have a vision guidance capability whereby an existing mark could be repainted accurately with little operator input. It is proposed to develop a vision system capable of identifying existing painted pavement markings and determining their dimensions, location, and orientation. This information would then be passed to a robotic painting device (currently under development) to enable it to accurately repaint the marking.

Literature Review

The previous work that has been done related to the analysis of images of roadway markings falls into two categories: The recognition of lane markings (i.e. lane lines and centerlines) and the recognition of symbols and messages (e.g. turn arrows, STOP messages, railroad crossings, etc.). The first area has seen a great deal of activity focused primarily on providing information for automated vehicle navigation (e.g. [1]), but with some applications to repainting [2]. There has been much less activity in the second area. One system was developed with the intent of recognizing markings that were incomplete, obscured, or damaged using a Hopfield neural network [3]. Another system was developed to perform automated surveys of roadway markings using in-vehicle cameras [4]. No system was found with the objective of guiding a robot to repaint existing roadway markings.

Previous work was also referenced while developing the image processing algorithms described in this report. Information on correcting fisheye lens distortion [5] was used to help develop the corrective algorithms, and information on projective transformation and Homography [6] was used in developing the translation between image coordinates and robot workspace coordinates.

Expected Benefits

The benefit of this research would be to significantly improve the capability of a robotic painting device to repaint existing pavement markings. Since over 75% of pavement painting operations involve repainting existing marks, this would dramatically improve the usefulness of such a device. Eventual users of a device using this technology could be city, county, state, and federal government agencies and private companies or contractors.

Intellectual Property Protection

The Office of Technology Commercialization at the University of Minnesota has determined that, although the robotic roadway painter concept does not appear to be patentable, it is still worth protecting since the technology could very likely be licensed and marketed to potential manufacturers. The most unique aspect of the painter will be the vision guidance system that enables it to repaint existing markings easily, and that aspect is based on the technology developed in this project. For this reason this report is focused on the results of the research rather than the details of the hardware or software.

Chapter 2. Methodology

The goal of this project was to design and build a vehicle-mounted image acquisition system capable of capturing images of existing roadway markings (turn arrows, STOP messages, railroad crossings, etc.) and extracting information from the images including the identity, dimensions, location, and orientation of pavement markings in the image (see Figure 2.1).

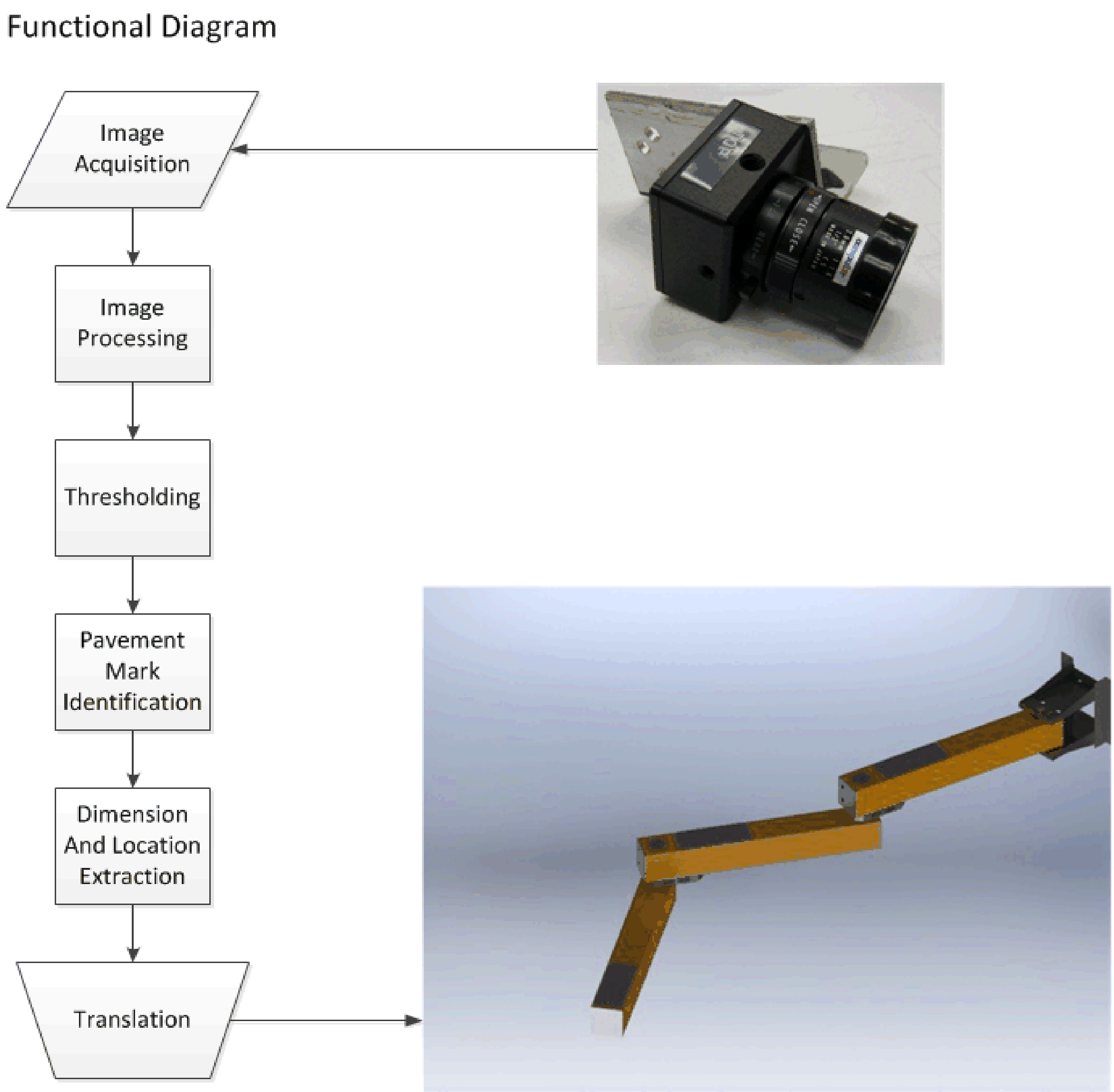


Figure 2.1: Functional diagram of system.

The work for this project was broken down into functional areas, and each of those areas was further subdivided into specific tasks. Table 2.1 shows the work breakdown for the project. The work done in each area is detailed in the sections that follow.

Table 2.1: Work breakdown structure.

Area	Tasks
Image acquisition	• Purchase image acquisition equipment • Capture images for development
Image processing	• Image preprocessing • Image segmentation • Object identification • Object sizing and location
Testing	Test image system for the following: • Processing capability • Identification accuracy • Location accuracy • Dimensional accuracy
Integration	• Translate image location information into robot coordinates • Transmit coordinates to the robotic painter control system

Image Acquisition

Image acquisition equipment was purchased and a vehicle mounting system for the camera was designed, built, and installed on a vehicle. The camera purchased was a Mightex Systems Model SCE-BG04-U monochrome CMOS camera with a 752 x 480 resolution and USB interface (see Figure 2.2). The camera was supplied with basic image acquisition software, and is powered by the USB port. A Dell Inspiron 15R laptop computer and a 10-foot USB cable were purchased to complete the system.. The camera was installed on a vehicle (see Figure 2.3) and the USB cable was routed into the vehicle cab and connected to the laptop to complete the mobile image acquisition system (see Figure 2.4). The system was used to capture images of existing roadway markings. Those images were used to facilitate the development, calibration, and testing of the software.

Figure 2.2: Mightex camera.

Figure 2.3: Vehicle with camera installed.

Figure 2.4: Laptop in vehicle.

Figure 2.5: Raw image of pavement marking.

Image Preprocessing

The goal of image preprocessing is to prepare the image so that a pavement mark can be recognized and located in the image. Figure 2.5 shows a typical raw image of a pavement marking. The image poses several problems for a recognition system. First, the camera uses a fisheye lens to capture a wide field of view, and that leads to non-linear distortion. The practical result of this is that lines that are straight in the real world appear curved in the image. To correct this distortion requires a mathematical transform between pixel locations in the distorted raw image and corresponding pixels in the corrected image (see Figure 2.6).

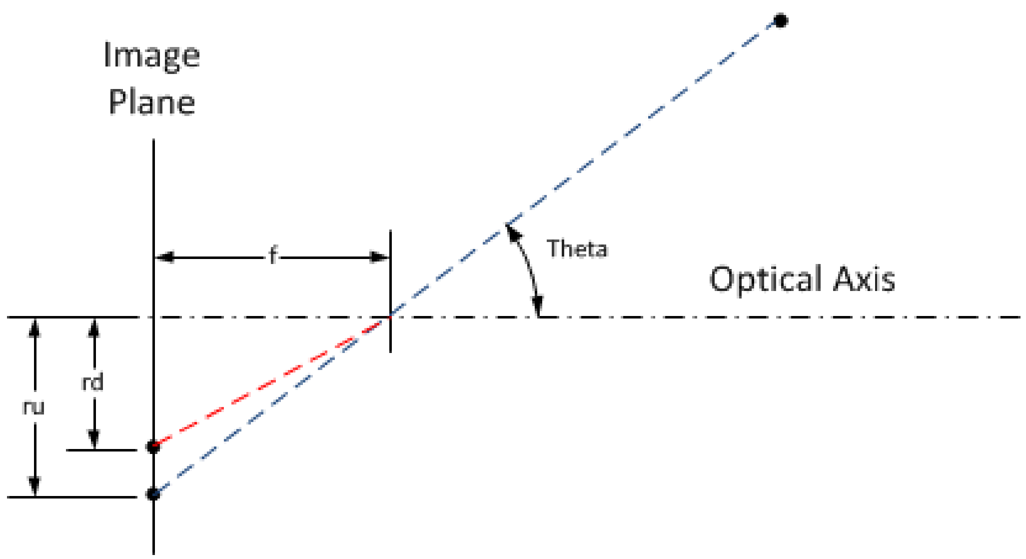


Figure 2.6: Fisheye lens geometry.

The standard model for a fisheye lens [5] is as follows:

$$r_d = 2f\sin\left(\frac{\theta}{2}\right)$$

Where:

r_d is the radius from the center of the image to a specific pixel
θ is the angle between a point in the real world the optical axis
f is the focal length of the lens

The location of the pixel in the raw image and the focal length of the lens are known, so the equation can be solved for the unknown angle:

$$\theta = 2\arcsin\left(\frac{r_d}{2f}\right)$$

Once the angle is known, simple geometry leads to:

$$r_u = f\tan\theta$$

Where:

r_u is the radius from the center of the image to the undistorted pixel

Each pixel in a distorted raw image can then be translated into an undistorted image using these equations. The result of doing so with a rectangular array of pixels in the raw image is shown in Figure 2.7.

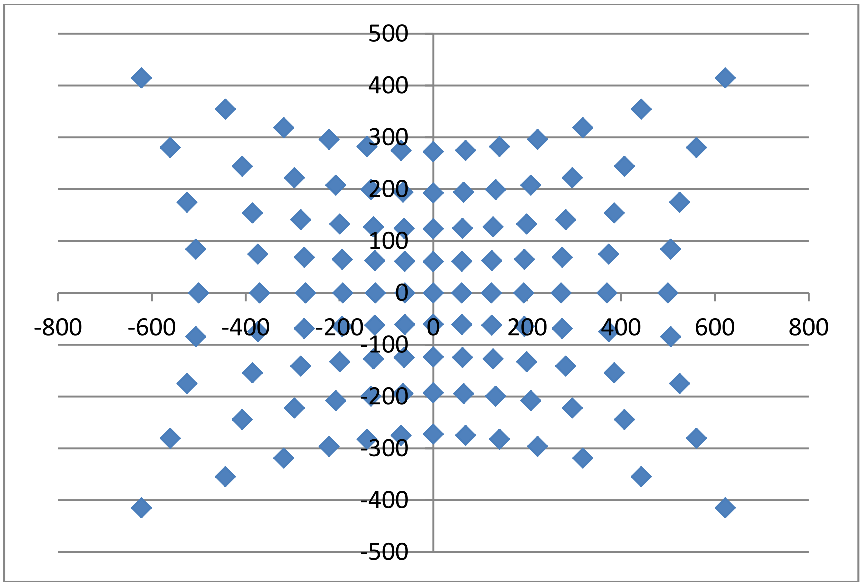


Figure 2.7: Effects of fisheye correction algorithm on rectangular pixel array.

The second problem is that the image represents an area much larger than what can be painted by the robot. This can be countered by simply clipping the image to an area that represents approximately one lane width and a distance about 12 feet in front of the vehicle. The robot workspace fits comfortably inside this area. Figure 2.8 shows the result of clipping the fisheye-corrected image.

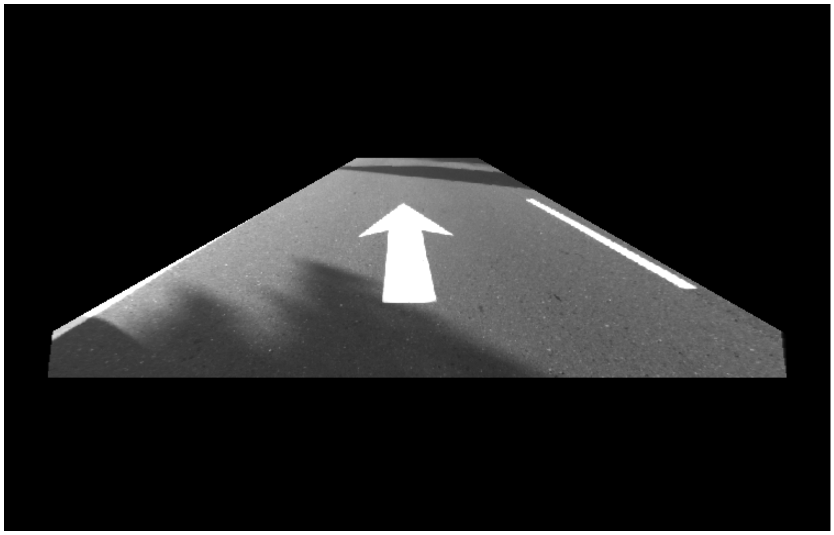


Figure 2.8: Fisheye corrected and clipped image.

Image Segmentation

The third problem is one of extracting the pavement marking from the background. Since the background is darker than the marking this can be done using a thresholding technique where pixels above a certain value in brightness are considered to belong to markings, and pixels below the threshold are considered to belong to the background. Figure 2.9 shows the result of thresholding the corrected and clipped image in Figure 2.8. Once thresholding is complete, the image is ready for the recognition and location tasks.

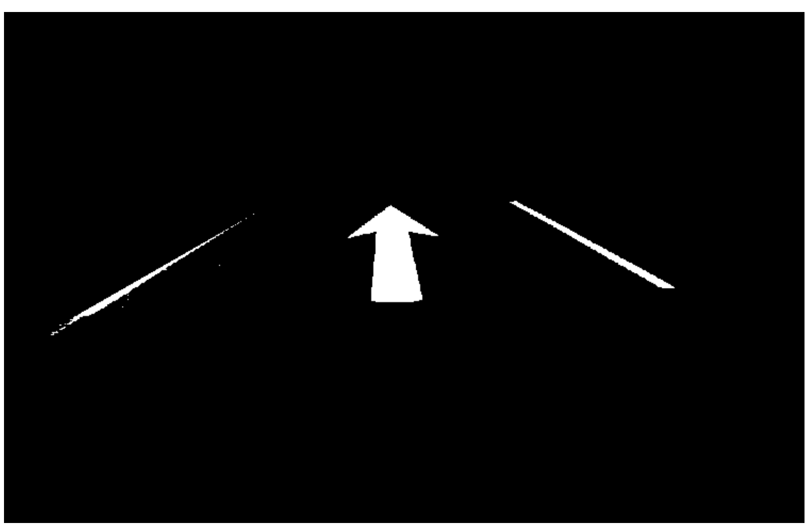


Figure 2.9: Image after thresholding.

Object Recognition

Once an object has been extracted from an image, it can be compared with representations of standard markings to determine if there is a match. A standard Backpropagation neural network was used for this task. Several images of each type of marking were gathered for this purpose, and those images were divided into a training set (used to train the network to recognize certain markings) and the test set (used to test the recognition accuracy). The neural network was then tested to determine the recognition accuracy.

Object Location

Once the marking extracted from the image is recognized it is a simple matter to locate it in the image. The extents of the marking are determined by finding the minimum and maximum values of X and Y for the pixels that represent the mark, and the center of mass can be found by calculating the average X and Y pixel values.

Integration with the Robotic Painter

Once the mark is identified and located in the image, that information can be used to estimate the position of the mark in the robot workspace. The robot painter is capable of painting standard roadway markings with geometry specified by MnDOT. Using the location and size information extracted from the image, the geometry of the mark can then be projected into the image, as shown in Figure 2.10.

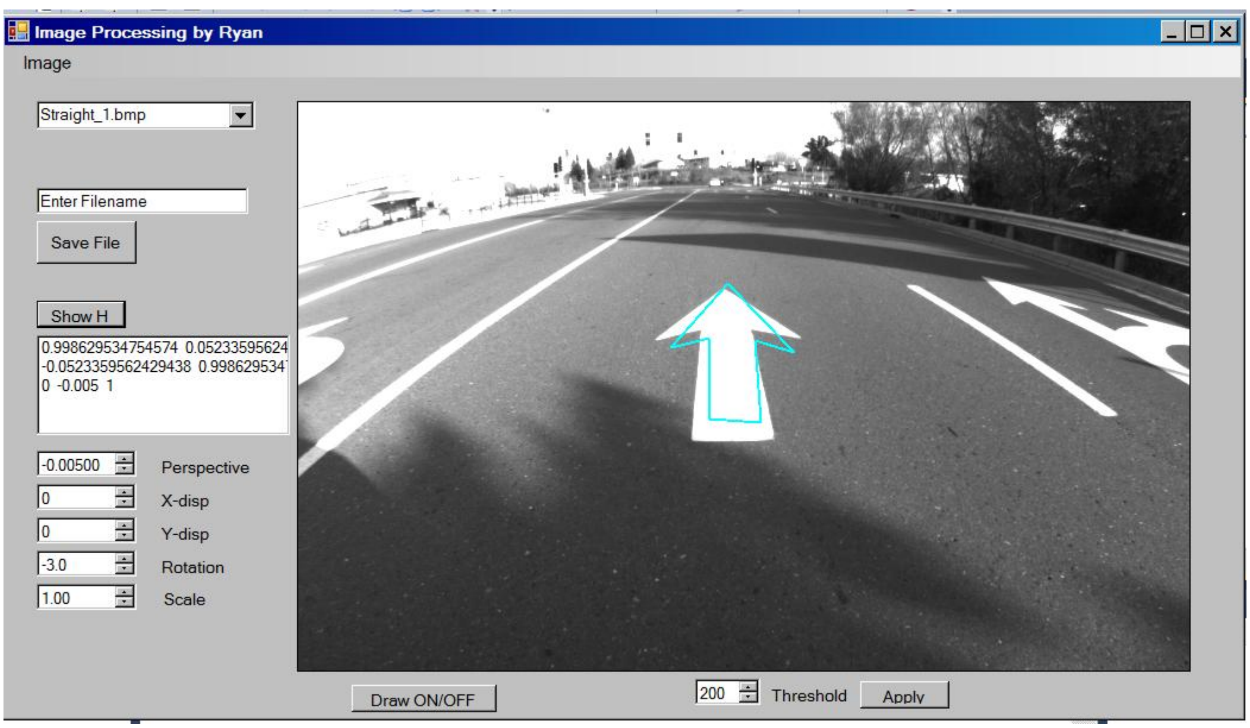


Figure 2.10: Initial projection of mark geometry into image.

This projection can then be corrected based on the appearance of the mark in the image. This correction is performed by adjusting the scale, the *x* and *y* displacement in the image, and the perspective distortion. This type of adjustment is known as a projective transformation [6]. Mathematically, a point (x_i, y_i) in the image is related to a point (x_m, y_m) in the pavement marking as follows:

$$\begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix} = \begin{bmatrix} H_{1,1} & H_{1,2} & H_{1,3} \\ H_{2,1} & H_{2,2} & H_{2,3} \\ H_{3,1} & H_{3,2} & H_{3,3} \end{bmatrix} \times \begin{bmatrix} x_m \\ y_m \\ 1 \end{bmatrix}$$

Where the matrix **H** is the Homography matrix.

The elements of the Homography matrix are detailed in Table 2.2.

Table 2.2: Homography matrix elements.

Elements	Effect
$H_{1,1}$ $H_{1,2}$ $H_{2,1}$ $H_{2,2}$	Rotation
$H_{1,3}$ $H_{2,3}$	Translation
$H_{3,1}$ $H_{3,2}$	Perspective
$H_{3,3}$	Scale

The elements of the Homography matrix can be adjusted until the projection of the mark in the image closely matches the appearance of the mark in the image. This adjustment can be done automatically to a point based on the representation of the mark that was extracted from the image. The resulting projection is shown in Figure 2.11.

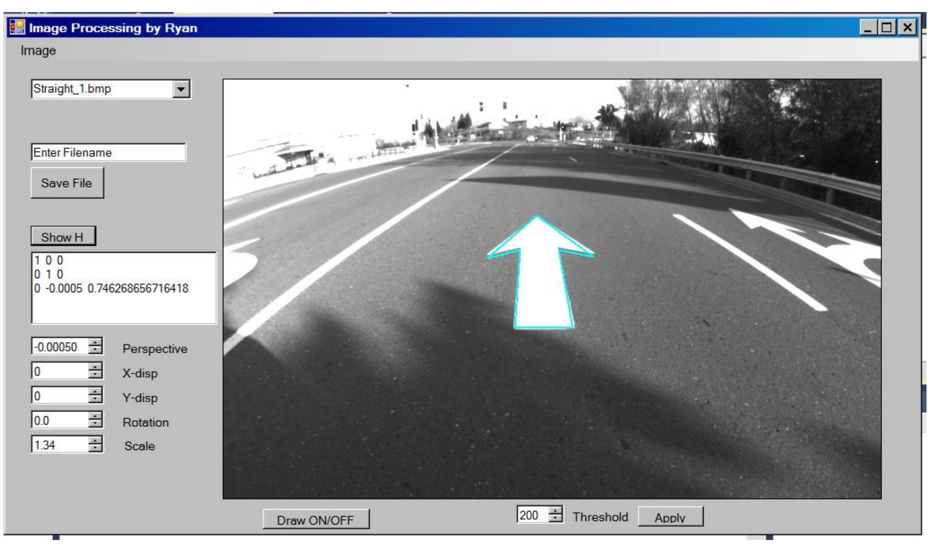


Figure 2.11: Corrected projection of mark geometry into image.

This projection can further be corrected by the operator using manual controls. Once the final H-matrix is determined, the inverse of the matrix can be used to determine the exact location of the mark in the robot workspace.

Chapter 3.   Results and Conclusions

Image Acquisition

Over 40 images of pavement markings were collected for test and development purposes. Examples of those images appear in Figure 3.1 at the end of this chapter. The images were captured on various days under various lighting conditions, and an attempt was made to capture images of clean markings as well as dirty or worn markings.

Image Processing and Segmentation

The image processing and segmentation steps as described in Chapter 2 were conducted on several images. After some testing and adjustments, the system was capable of successfully performing the steps of fisheye correction, clipping, and thresholding on all of the test images.

Object Recognition

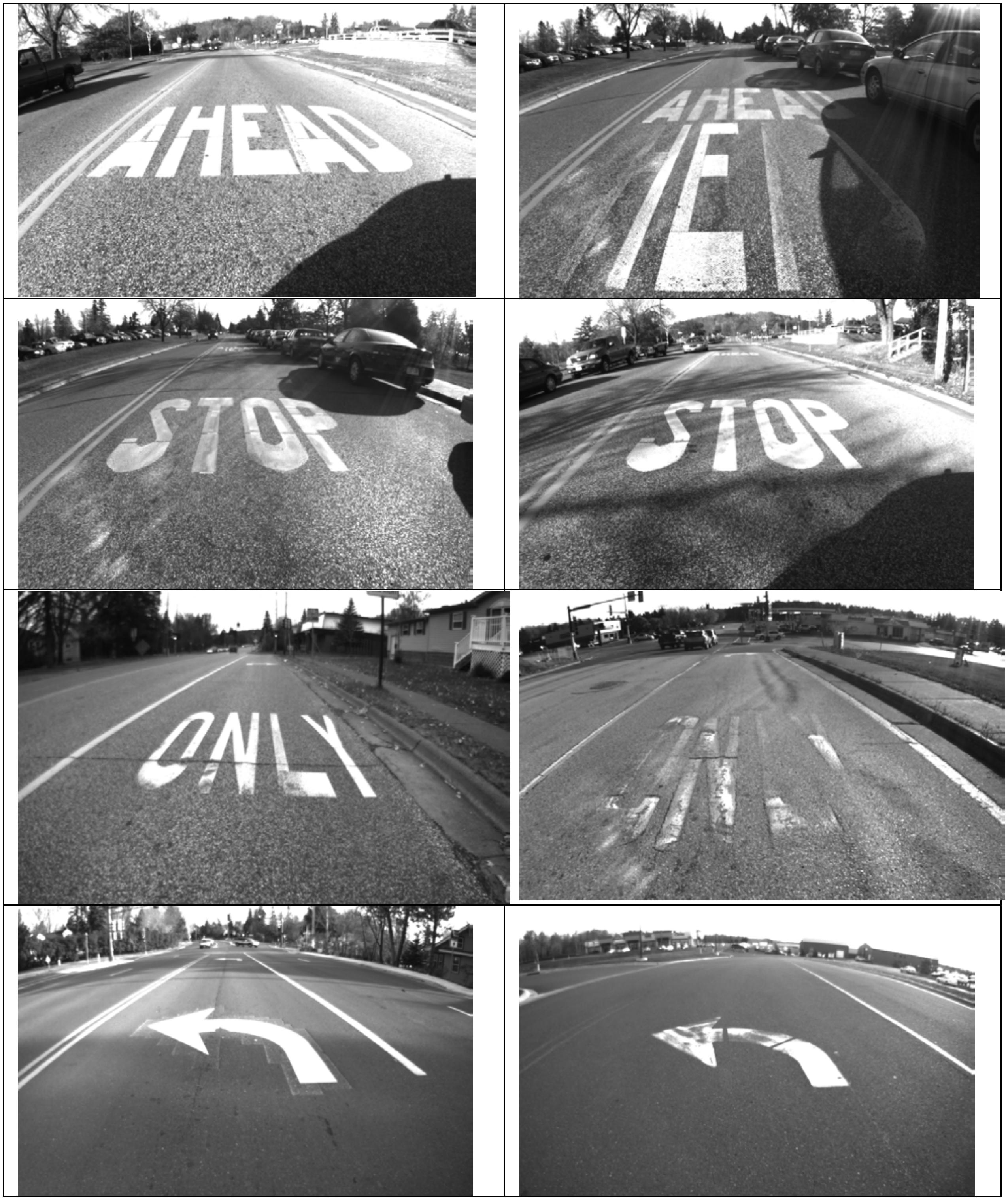
A Backpropagation neural network was used for the recognition task as explained in Chapter 2. Once the network was trained on the images in the training data set, recognition tests were performed using the images in the test set. The recognition accuracy was approximately 90%. The markings that failed to be recognized were either very dirty or worn.

Object Location and Translation

The object location and identification information were used as described in Chapter 2 to determine the projective transform between the image and the robot workspace. The resulting projection of the mark into the image required only minor manual adjustment prior to being used to determine the location of the mark in the robot workspace.

Conclusions

Repainting existing roadway markings (turn arrows, STOP messages, railroad crossings, etc.) is an important task for transportation maintenance organizations. MnDOT estimates that over 75% of symbol and message painting is the repainting of existing markings. It would be extremely valuable for an automated painting system to have a vision guidance capability whereby an existing mark could be repainted accurately with little operator input. In this project a vision system was developed that is capable of identifying existing painted pavement markings and determining their dimensions, location, and orientation. Techniques were also developed whereby this information could be used to determine the location of the marking in the workspace of a painting robot to enable it to accurately repaint the marking. The vehicle-mounted robotic painter is still being built and tested, so final test results will not be available until the vision system can be completely integrated with the painter and the two can be tested together. The accuracy of the projection produced using the techniques developed in this project would suggest that the final system will be capable of repainting pavement markings almost exactly where they appear on the roadway. Expected benefits of the deployment of a vision-guided robotic painting device include improved operator safety, improved productivity, and improved flexibility in roadway marking and repainting operations. Eventual users of a device using this technology could be city, county, state, and federal government agencies and private companies or contractors.



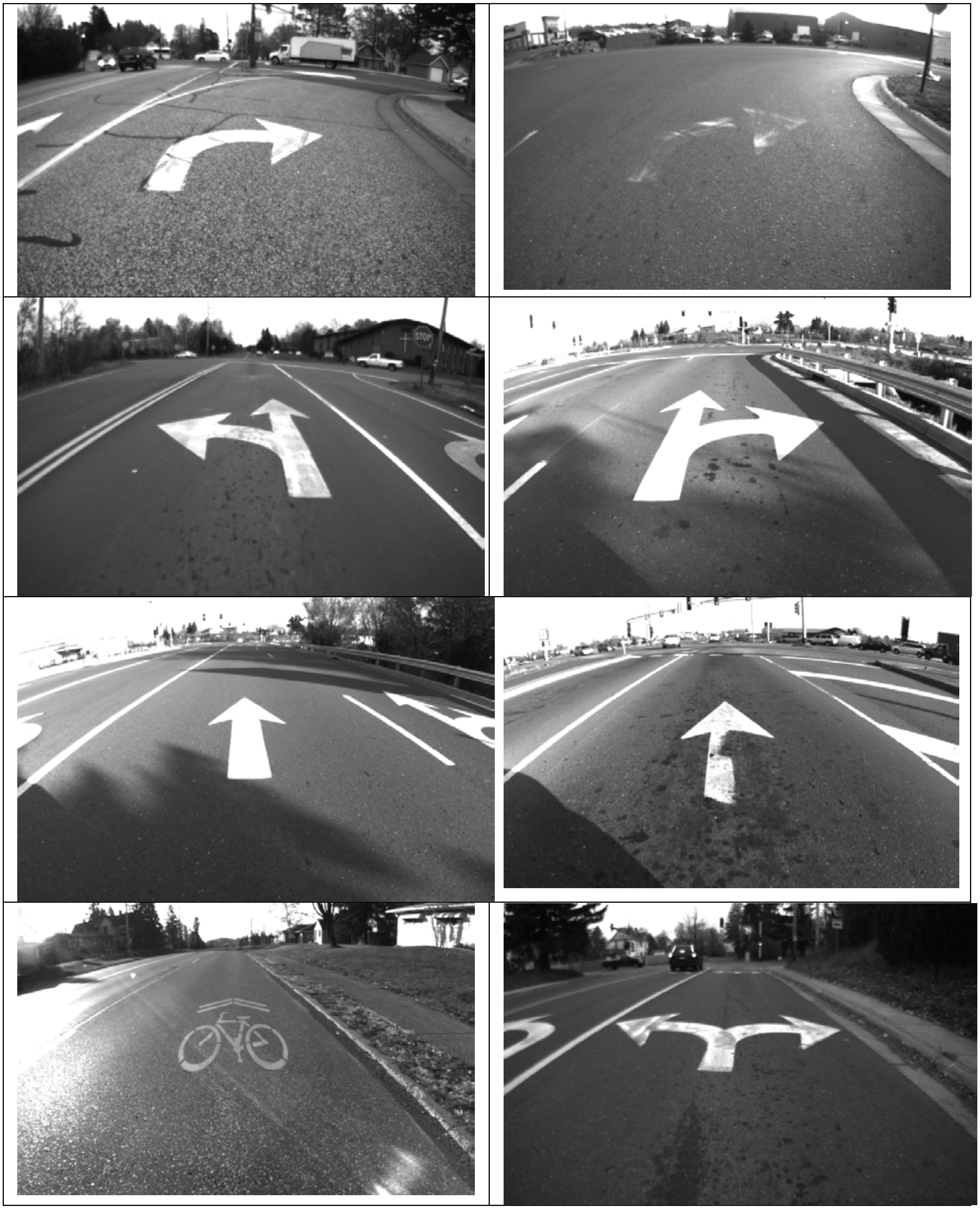


Figure 3.1: Example images.

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