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Team 5: Prototype of a Microsurgical Tool Tracker
CIS 2 – EN.600.646
3/28/2013
Paper Review

Paper Title: Fast and Inexpensive Color Image Segmentation for Interactive Robots
Authors: James Bruce, Tucker Balch, Manuela Veloso
Published: IEEE International Conference Intelligent Robots and Systems, 2000

Project Summary:
The goal of our project is to create a prototype of a microsurgical tool tracker to be used for eye surgery. Specifically, we will design a goggle-like device to be placed over the eye to house four cameras. Optical RGB images will be processed through a calibration, detection, and tracking pipeline to extract tool tip coordinates with respect to the trocars. At the end of the semester, the goal is to prove the feasibility of utilizing optical trackers in ophthalmic surgery.

Necessary Background:
In 2009, it was shown that ophthalmic surgery had the highest number of incorrect procedures compared to any other procedure [1]. Ophthalmic surgery is a type of microsurgery that requires great surgical skill because the small-scale surgery requires great precision, accuracy, and efficiency. As such, surgeons would benefit from positional feedback of the tool [2]. Specifically, positional feedback has the potential to monitor surgical performance, assess surgical skill, and improve surgical safety [2].

Although optical trackers are prone to occlusion, they allow for better tracking accuracy when compared to electromagnetic trackers [3]. Therefore, in choosing to use an optical tracker, we must prepare software that is flexible to occlusion while maintaining accuracy. In order to calculate tool position, there are 3 major computer vision components: calibration, detection, and 3D point reconstruction. The paper reviewed here will focus on a fast, computationally inexpensive detection method.

Paper Selection and Relevance:
One important step in tool tracking is to accurately detect the tool. While camera calibration and 3D point reconstruction is relatively well defined, creating segmentation algorithms that are as robust as the human visual system has been difficult. For the purpose of our project, we desired a fast, computationally inexpensive color segmentation method that was robust to luminance, and relatively easy to implement. The segmentation method described in this paper is a clean, elegant solution for detection using color markers.

Summary of Problem and Key Result:
Currently, most systems employing real-time color-based segmentation are either implemented in hardware or specific software systems that take advantage of domain knowledge to attain efficiency [4]. This paper proposes a novel solution that utilizes algorithm efficiency for fast color image segmentation with common image capture and CPU hardware. Specifically, the paper describes a system capable of tracking several hundred regions for 32 different colors at 30 Hertz using general-purpose commodity hardware.

Significance of Key Result:
Using the techniques described in this paper, it is possible to implement real-time tracking without expensive hardware or overly complex algorithms. This has the potential to make optical tracking an affordable, viable option without sacrificing accuracy. There are many significant applications for this segmentation technique beyond our microsurgical tool tracker project.

Specifically, they tested their implementation for a group of inexpensive autonomous robots based on the Probotics Cye platform. These robots were based on commodity hardware to keep cost low and simple, but still required high performance to serve as a hazard sensor. Another successful application was for Carnegie Mellon's entry into the RoboCup-99 legged-robot league. This is a contest where robots play a game of soccer; the robots must recognize and process information about their surroundings in order to win the game.

Technical Approach:
A. Thresholding
First, YUV matrices are extracted for each pixel of the images. The YUV color space is more robust against luminance than RGB. The group utilized a system that provided YUV colors in hardware to avoid performance penalty of a software color space transformation.
Next, logical AND gates were implemented to classify each pixel into a color class. This is an important and elegant solution because it only requires two logical AND operations, rather than 192 comparisons that would be standard for other algorithms testing for 32 colors. In order to accomplish this, each color was defined with a binary matrix where a certain range of Y, U, and V ranges were classified as a color. For example, blue is:
YClass[] = {0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1}
UClass[] = {1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0}
VClass[] = {0, 0, 0, 1, 1, 1, 0, 0, 0, 0}
Therefore, if a pixel had [Y, U, V] of [8, 2, 4], it would be classified as blue. Finally, instead of defining each color as a separate matrix, the group took advantage of integer arrays and put 32 colors into the same matrix, where each value could be up to 32 digits long.

B. Connected Regions

In order to increase efficiency, the group computed a run length encoded version for classified images. By grouping similar adjacent pixels as a single ‘run’, subsequent data use can operate on runs instead of pixels. The merging method is a tree-based union find that has a linear time bound. Specifically, the algorithm searches from left to right for similar pixels and groups them together. Then, a second run length encoded search is performed top down to connected rows of pixels together. Below is a figure that describes this procedure of grouping after run length encoding.

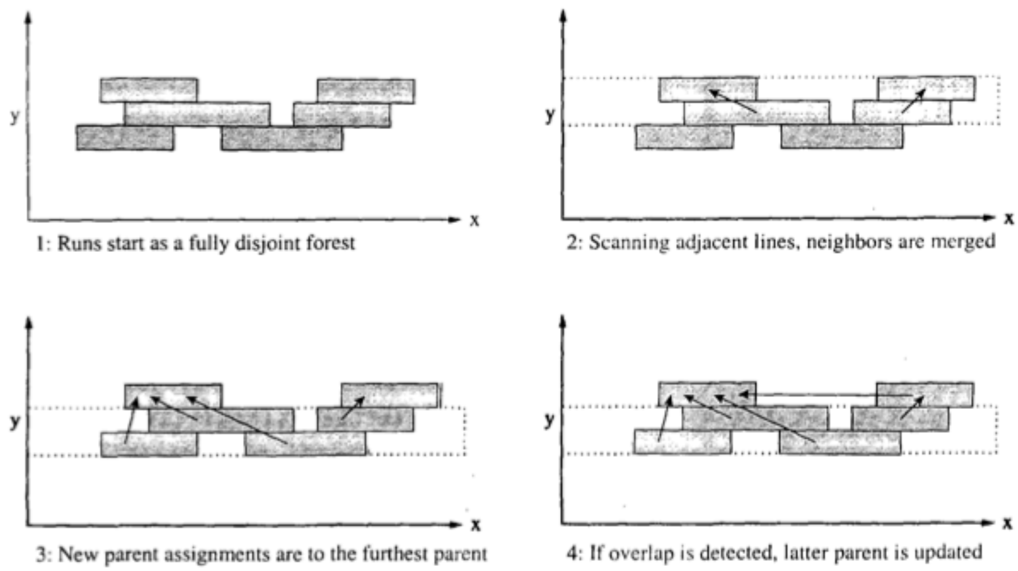

Figure 2: An example of how regions are grouped after run length encoding.

C. Density-Based Region Merging

Finally, the method described in this paper accounts for occlusion and errors generated in bottom up region generation by employing a density-based region merging. In their approach, pairs of similar, nearby objects are merged based on some ‘grouping force’ that can be varied depending on what is appropriate for objects of a particular color. In the most basic case, if a string of pixels were misclassified as a different color, the area separating the two regions would be small enough that the density of the merged region would still be above some threshold.

Assessment:

The fast, inexpensive, and simplicity of this segmentation algorithm opens up opportunities to create tracking systems that do not require specialized hardware or system-specific software. This is particularly significant for optical tool tracking applications that require real-time, precise tracking on a budget. Specifically, our project to build a prototype of a microsurgical tool tracker for eye surgery will greatly benefit from employing this fast blob color segmentation technique.

This paper did a great job explaining the technical aspects of implementing their segmentation technique. Their solution is elegant and practical, and generally well thought out. It is written in a way that a reader with only a basic understanding of computer vision can grasp their concept; this is refreshing from the jargon that is usually found in papers.

I would have appreciated it if the paper had delved into more details about the hardware set up necessary to directly acquire YUV color space images. For our project, we will employ a color space transformation function, which will be less efficient, unless we can gain more expertise on this matter.

Also, it is great that this segmentation technique has been tested in several real-life applications. However, it would be interesting to see more medically relevant applications, and statistics that compare its performance speed and accuracy to other segmentation techniques. Perhaps in the future, a report will be made on the major segmentation methods that have been suggested in order to get a concrete list of pros and cons.

References:

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[4] J. Bruce, T. Balch, and M. Veloso, "Fast and inexpensive color image segmentation for interactive robots," in Proc. IEEE Intl. Conf. Intell. Robot. Syst., 2000, pp. 2061–2066.