Simple Multi Function Vision System for 3D Data Acquisition*

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Abstract

We have developed a simple multi function vision system for 3D data acquisition for a wide range of applications in robotics and automation. The system uses one CCD video camera and an active directed laser light source based on a direct drive spherical pointing motor (SPM). The anatomy of the system and algorithms used are described. System calibration methods and measurements of accuracy of the outputs are presented. A list of applications is shown.

1 Introduction

The three main approaches known for 3D data acquisition are stereo vision, laser range-finder and vision system with structured light. Each of these approaches has its own tradeoffs. In our system, we emphasize real time performance, simplicity, reliability, low cost and adaptability to a wide range of applications.

From this point of view, the conventional approaches have significant drawbacks. Stereo vision systems are either computationally expensive or have been found to be unreliable in experiments [5][2][4]. Laser range finders either acquire only one dimensional distance data or are complex and expensive. Furthermore, combining range data with an image is still an open research problem. Vision systems utilizing structured light require a straight line or special constant regular structure covering the entire field of view [5].

Our system is capable of randomly accessing points within the field of view as well as emulating different kinds of structured light patterns. This flexibility allows the system to work in real time simply and inexpensively.

2 System Anatomy

The hardware in our system consists of a single CCD video camera for image acquisition and a direct drive spherical pointing motor (SPM)[12] carrying a diode laser (see figure 1) for generating structured light patterns. A computer workstation coordinates the vision system through a video frame grabber and a serial line connected to a microcontroller that drives the SPM. The system in this configuration can be used for 3D data acquisition and as visual feedback for SPM calibration. Figure 2 shows a schematic of the hardware elements in our system.

3 Algorithm for 3D Data Acquisition

First, a target point on the camera image is selected. This can be done either by specifying a pixel coordinate or by locating a mark that has been placed in view of the camera.

Once the goal target has been specified, the next task is to point the SPM so that the laser beam's spot lies on the target point. This is accomplished by iteratively locating the center of the laser spot in the video image and determining the difference between the spot location and the goal target. If the difference is not zero then the SPM is commanded to move toward the target and the process is repeated until the laser spot reaches the goal target.

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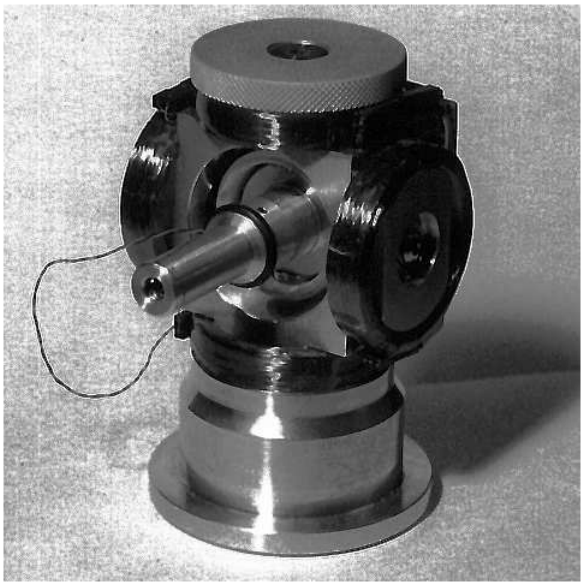

Figure 1: This prototype Spherical Pointing Motor (SPM), built by Fred Hansen, has a 65 degree conical workspace. The rotor limb contains a cylindrical permanent magnet which is moved by applying currents to the horizontal and vertical sets of coils. The position of the limb is measured by four Hall effect sensors located on the back plane of the SPM. The laser is inside the alumninum limb.

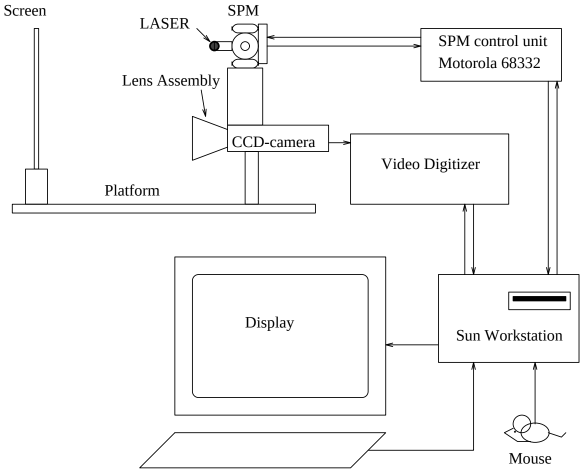

Figure 2: Schematic diagram depicting the hardware used in our investigation.

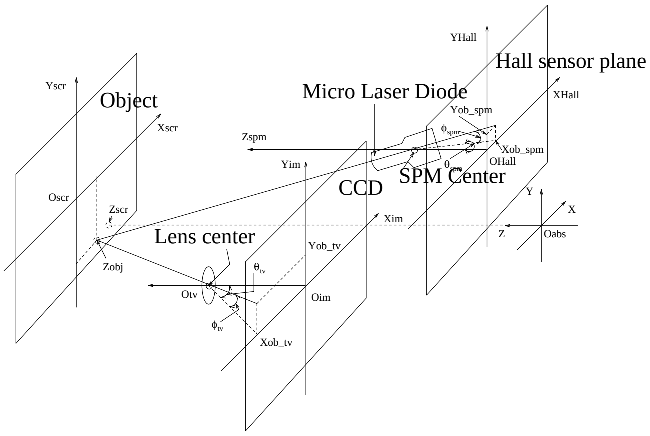

Figure 3: Coordinate frames used in triangulation calculations.

Once the goal target is reached, the orientation of the laser beam is calculated from Hall effect sensor data in order to perform triangulation. Figure 3 shows the coordinate frames used in the triangulation calculations. The following equations are used for triagulation:

$$
\begin{aligned}
Z_{obj} &= \frac{Y_{spm} - Z_{spm}\tan\phi_{spm}}{\tan\phi_{spm} - \tan\phi_{tv}} \\
\tan\phi_{spm} &= Y_{ob\_spm}/B_{spm} \\
\tan\phi_{tv} &= Y_{ob\_tv}/focus \\
Y_{ob\_spm} &= Y_{spm\_cu}COF_{spm\_y} \\
Y_{ob\_tv} &= Y_{ob\_pixel}COF_{tv\_y} \\
COF_{spm\_y} &= \frac{((Y_{spm} + (Z_{scr} - ZO_{tv})\tan\phi_{tv})B_{spm}}{(Z_{scr} - Z_{spm})Y_{spm\_cu}}
\end{aligned}
$$

The conventions used in the above equations are the same as in figure 3 with the following additions:

B_{spm} - distance between SPM center ans SPM Hall sensor plane

$focus$ - TV-camera lens focus

Y_{spm_cu} - SPM back end coordinate in Hall Sensor units

Y_{ob_pixel} - Y coordinate of object in image pixels

OCF_{spm_y} - translation coefficient from Yaxis Hall units to metric sizes

COF_{tv_y} - translation coefficient from Yaxis image pixels to metric sizes

4 Calibration

Accurate 3D data acquisition based on triangulation requires accurate data for the geometry of the system elements. The relative geometry of the camera, SPM and screen are easy to measure, however the orientation of the SPM rotor limb is not easily derived from the arbitrary Hall effect sensor units that the SPM controller returns. Hence the most important calibration problem involves accurately mapping Hall effect sensor units into the pan and tilt angles of the rotor.

In our experimental setup, only a small portion of the SPM's workspace falls within the field of view of the camera. One good consequence of this is that the region of Hall sensor values visible to the camera is relatively linear and can be fit well with segments of linear functions.

4.1 Camera Calibration

TV camera calibration is performed by locating the laser spot on a test screen with special marks on it [1]. Based on the known geometry of the camera, SPM and screen, angle position of each point in the field of view can be determined.

4.2 SPM Calibration

Calibrating the SPM presents some difficulties. The Hall effect sensors used in the SPM for feeback have a relatively linear response as a function of magnetic flux through the sensor, but the value of the flux is substantially non-linear. Functions for the magnet flux exist, but are quite complicated [8][9][10].

To calibrate the SPM, a flat screen is placed a known distance from the SPM and camera in order to derive the SPM limb angles by triangulation. To calibrate the SPM along the field of view of the camera, we constructed a piecewise linear function mapping Hall effect sensor units into angles. The boundary points for each linear piece were chosen by the following procedure: first we choose several test points in the camera image and then performed lpt sequences [3][6][11] (Note: these sequences have special uniformity distribution properties so we can choose additional points with out repeating).

For several points within one linear segment, we calculate the distance between the true head position (determined via known system geometry and the location of the laser beam in TV image) and the linear segment. If the distance falls outside a tolerace of 0.01 degrees then either the linear coefficients are adjusted or a new boundary point is chosen and the linear segment is split in two. The above process is then repeated on each new linear piece.

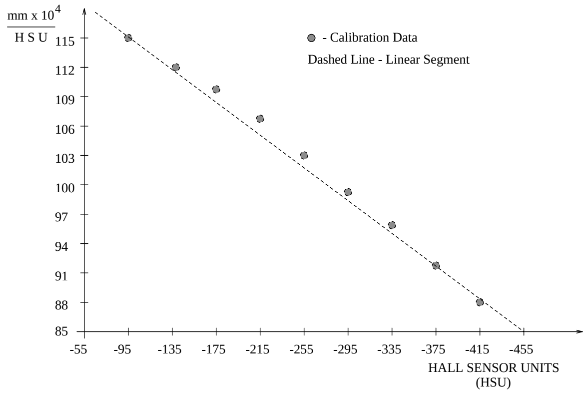

Figure 4: One linear segment of the calibration function showing a comparison between actual SPM position and the linear approximation

5 Experimental Results

We conducted our tests in our indoor Laboratory with ambient light and surrounding objects. Under these conditions, we found the working range of our 0.1 mW laser to be from 0.5 to 10 m. The accuracy of the experimental 3D data acquisition fell within 0-5% of the measured distance. This accuracy was achieve using a 9 segment piece-wise linear calibration covering the entire image the TV camera field of view (about 15 degrees). An example of a linear calibration function within one segment is shown in figure 4.

We investigated both horizontal and vertical relative displacement between TV camera and light source. We found that vertical displacement yields results of higher accuracy.

5.1 Error Analysis

There are several sources of error in our setup. Figure 5 shows the distribution of errors contributing to an overall 3% error found in measuring z distance.

The most significant source of error is the video digitizer used for image acquisition. The flaw is not in the resolution of the digitizer but rather in its inability to consistently start sampling from the same scan line of each video frame. This results in an uncertainty in the location of the center of the image by a few pixels.

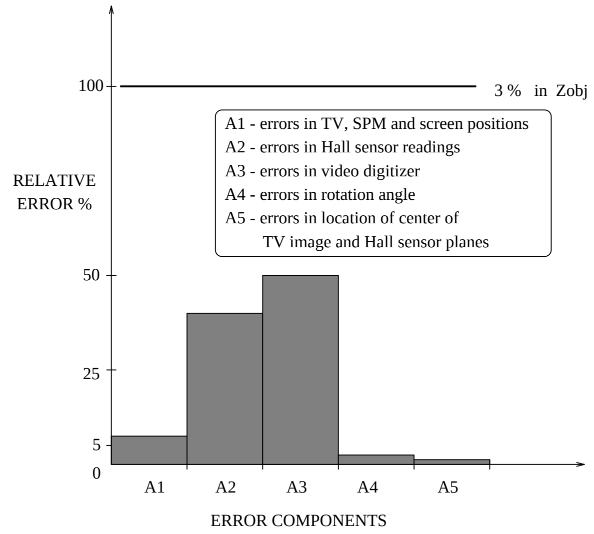

Figure 5: Breakdown of error contributions to overall 3% error in Z distance calculations along the Y direction

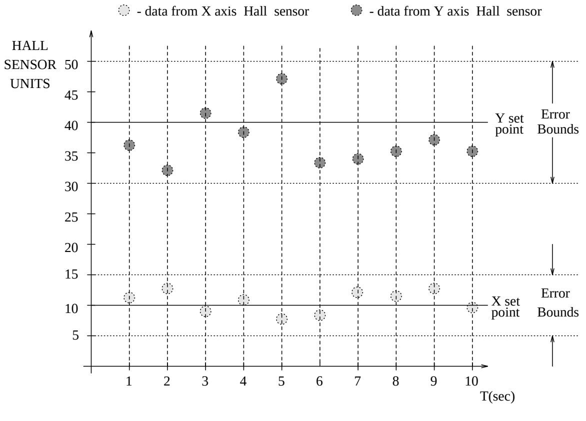

Figure 6: A comparison between Hall sensor records on X and Y axis.

The next most significant source of error is in the Hall effect sensor readings. Figure 6 shows the fluctuation in the X axis and Y axis Hall effect sensor readings.

Compared to the digitizer and the Hall effect sensors, all other sources of error (see figure 5) contribute relatively little to the overall error.

6 Conclusions and Further Work

In our error analysis (see figure 5), we found that the largest error contributions were due to inaccuracies in the video digitizer and in reading the Hall effect sensors. This suggests that our system could attain significantly improved precision with only moderately better hardware.

The characteristics of the multi-function vision system system make it appropriate for use in self-contained mobile robots, manipulators, and rapid prototyping for industry, medicine and the arts.

The current technology in direct drive actuators [13] suggests that our system can be scaled to small sizes. In fact SPMs of sub-millimeter size have already been fabricated [7].

We plan to construct a Micro Random-Access Laser Rangefinder based on the SPM. This new device will allow a surgeon to obtain range information to objects visible in micro TV camera images tramsmitted from inside the body during microsurgery. Often surgeons find the TV images confounding due to lack of depth information, but if we place the SPM with a micro-laser near the camera, then we can point the laser at any “pixel” in the camera image and determine the 3-dimensional coordinates of that point.

We will continue to investigate and improve our system in several ways. We plan to improve the video and SPM sensor subsystems in order to reduce our most significant sources of error. We plan to apply improved SPM control algorithms that we have developed to increase the 3D sampling rate of the system and to simplify calibration.

We are concurrently investigating several other applications for the SPM. We are developing an undergraduate curriculum in Robotics and Real-Time Control using the SPM and building Ada cross-compilers based on the GNAT compiler technology.

The contents of the course we propose will integrate both hardware and software topics, and include substantial programming experiments. Each course unit combines some aspect of embedded system design and programming with some features of Ada9X, in the context of a specific experiment with one of the robotics devices, many involving the SPM. A final project is the implementation of a complex set of behaviors by one or more devices, which can include a vision sensor SPM 3D data aquisition subsystem.

The low cost of the actuators is expected to have a significant impact on robotics education, because they can be disseminated widely to universities and technical schools.

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References

[1] Narendra Ahuja and A. Lynn Abbott.
Surfaces from dynamic stereo: Integrating camera vergence, focus and calibration with stereo surface reconstruction.
IEEE Pattern Analysis and Machine Intelligence, 1990.

[2] Yves Demorean.
A stereoscopic vision sensor for robotics: use design and calib ration.
In *Proceedings of the 15th Symposium of International Robotics*, 1985.

[3] P.L. Kalantarov and L.A. Ceytlin.
Inductance Calculation (in Russian).
1986.

[4] Takeo Kanade.
Three-Dimentional Machine Vision.
Carnegie Mellon University, 1987.

[5] G.P. Katys.
Processing of Visual Information.
Moscow, Mashinistroenie, 1990.

[6] V.L. Chechurin K.S. Demirchan.
Electric Magnetic Fields Computation.
Visshaya Shkola, 1986.

[7] Jack W. Judy Richard S. Muller and Hans H. Zappe.
Magnetic microactuation of polysilicon flexure structures.
Technical report, Department of Electrical Engineering and Computer Sciences, University of Berkeley, 1994 Solid-State Sensor and Activator Workshop, June 1994.

[8] I.M. Sobol.
Infinite uniform distributed sequences in calculation mathematics (in Russian).
Technical Report 22, Keldysh Institute of Applied Mathematics USSR Academy of Sciences, 1974.

[9] I.M. Sobol and Ur.L. Levitan.
Making points uniform distributed in multi dimentional cube (in Russian).
Technical Report 40, Keldysh Institute of Applied Mathematics USSR Academy of Sciences, 1976.

[10] Sergey M. Sokolov.
Definition of the marker and detecting its moving in the field of view of the photometric system (in Russian).
Technical Report 97, Keldysh Institute of Applied Mathematics USSR Academy of Sciences, 1980.

[11] T.A. Tatur.
Electric Magnetic Field in Real Mediums.
Visshaya Shkola, 1976.

[12] Richard S. Wallace.
Miniature direct drive rotary actuators II: Eye, finger and leg.
Robotics and Autonomous Systems, 48:76, 1995.

[13] Richard S. Wallace and J.M. Selig.
Scaling direct drive robots.
Technical Report 669, New York University, Computer Science, August 1994.