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Design and Analysis of an Absolute Non-Contact Orientation Sensor for Wrist Motion Control

Harry Garner*, Martin Klement†, and Kok-Meng Lee*, *Member, IEEE*

Abstract*–In this paper, aspects of the design and analysis of a vision-based non-contact absolute orientation sensor with application to wrist-like actuator motion control will be presented. This work is primarily motivated by the need for the measurement of the absolute orientation of a spherical rotor present in wrist-like actuators for the motion control of such systems. Current orientation measurement approaches increase the complexity of the mechanical structure through additional contact with the spherical rotor. To eliminate this additional complexity, a non-contact vision-based technique that realizes an absolute orientation measurement using a specially designed grid pattern that allows the absolute orientation information to be encoded onto the spherical body has been developed. Aspects of the design and implementation of this specially designed grid pattern will also be discussed. Improved techniques for transferring the grid pattern to a spherical object will be presented, and issues related to the use of such a vision-based system for motion control will be discussed.

I. INTRODUCTION

A measurement system is a vital part of any control system because it makes it possible for the control system to determine when a specified control goal is being met. Currently, there are many types of measurement systems available that are capable of measuring the relative and absolute position for a wide variety of applications. Two of the most common types of measurement devices are the linear and rotary optical encoder. Relative and absolute forms of these devices are readily available and can be used effectively in many control applications.

One important aspect of these types of encoders is the fact that they may require some contact with the object to be measured, and in many cases the structure must be modified to incorporate them. For certain applications that involve more complex measurements, such as the measurement of the orientation of a spherical body, the modifications required to the structure of the system add inertia and friction that may effect the performance of the overall system, which is undesirable. Figure 1 shows an image of a Variable Reluctance (VR) spherical motor developed at Georgia Tech, which is a wrist-like actuator that provides three-degree-of-freedom orientation positioning in a single compact joint. It contains a spherical rotor whose absolute orientation must be measured so that its orientation may be controlled in a desired fashion. The current orientation measurement system uses three single axis rotary optical encoders mounted onto special guiding structures to couple the orientation of the rotor to the encoders as shown on the VR spherical motor in Figure 1. These additional guiding structures add complexity to the overall mechanical system and may reduce the performance that can be achieved. To overcome these limitations, a vision-based non-contact absolute orientation measurement approach has been proposed that utilizes a specially designed grid pattern to encode the absolute orientation information onto a spherical body [1].

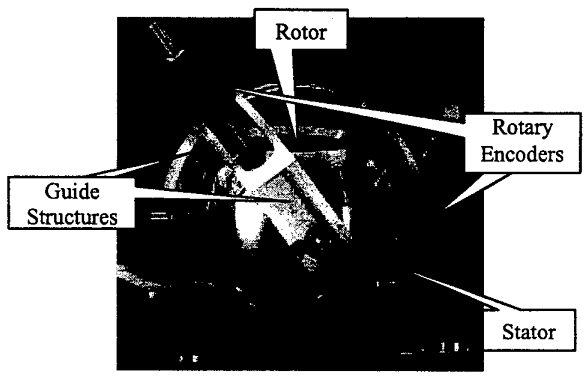

Figure 1. VR Spherical Motor

Figure 2 shows a drawing of the vision-based orientation sensor applied to the VR spherical motor. The angles that define the orientation of the rotor are shown (A, Θ, Φ), and the spherical grid pattern is shown. Two significant coordinate frames are also defined with a space fixed frame fixed to the stator given by XYZ, with X along the vertical. The other frame is fixed to the rotor given by *uvw*, with *u* along the rotor shaft. The objective of absolute orientation measurement system is to determine the transformation matrix, which describes the absolute orientation between these two frames. To solve this absolute orientation problem, an incremental spherical grid pattern was proposed as shown in Figure 3. The objective of this grid pattern is to encode the orientation information into a form that can be read by a vision system. However, the incremental nature of this grid

* The authors are with the George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405.
† Lexmark Inc., Louisville, KY.
For more information, contact kokmeng.lee@me.gatech.edu

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pattern makes absolute orientation measurement difficult to achieve [1].

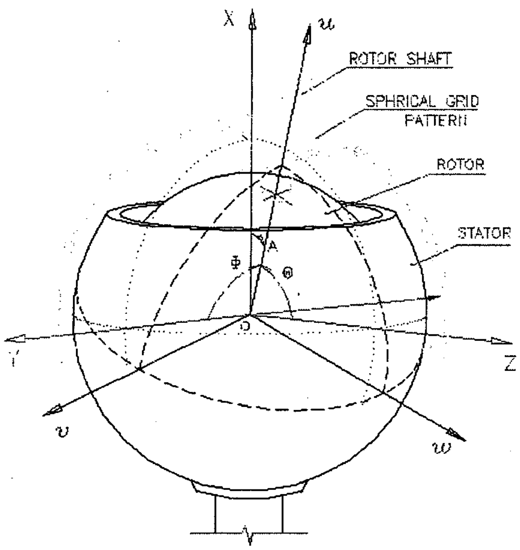

Figure 2. Vision-based Orientation Sensor Concept [1]

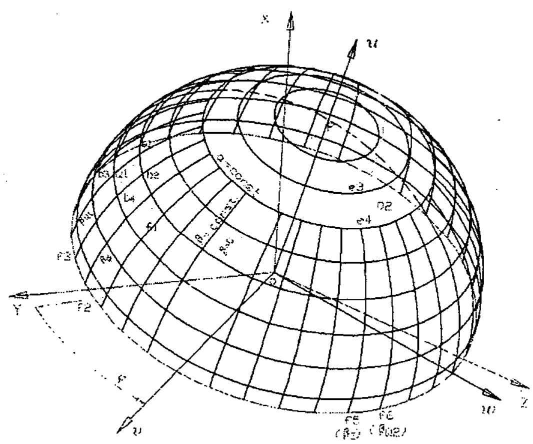

Figure 3. Incremental Spherical Grid Pattern [1]

In this paper an extension of this vision-based absolute orientation measurement system will be presented that uses a specially designed grid pattern to encode the absolute orientation onto a spherical body. First, background related to vision-based measurement will be presented. Aspects of the design and implementation of the specially designed grid pattern will also be discussed. The image analysis techniques and procedure used to extract the absolute orientation information will also be presented. Finally, issues related to the use of such a vision-based system in a motion control system will be discussed.

II. VISION-BASED MEASUREMENT

Vision-based measurement, also called optical gauging, is a technique for making displacement measurements based on the relative position of some type of pattern in the field of view of a vision sensor such as a CCD camera. This type of sensing is used in many areas such as the alignment of contact lenses using fiducial marks, automobile wheel alignment, and alignment, docking and assembly tasks related to the construction of the International Space Station [2][3][4]. In this work, vision-based sensing has been extended for use in the absolute orientation measurement of a spherical object allowed to move with three degrees of freedom. Stevenson and Jordan[5] developed an absolute position measurement system using the optical detection of coded patterns with the capability of locating the displacement of automated guided vehicles in two dimensions. Their system was only capable of measuring displacement in two dimensions and not rotation. The vision-based orientation sensor developed in this work utilizes a special grid pattern that uses ideas similar to those of Stevenson and Jordan.

Vision-based measurement systems are especially well suited for absolute position or orientation measurements because it is possible to encode this absolute information into a special pattern that is imaged by the vision system. This aspect gives vision-based systems a significant advantage over conventional measurement systems. Vision-based systems are often more flexible because they can measure multiple degrees of freedom with a single image measurement that would require a more complex configuration of conventional single axis sensors. Finally, vision-based systems typically do not require any contact with the object to be measured, which allows minimal interference and eliminates any performance degradation due to contact with it. With all these important benefits, vision-based systems have a significant limitation in that they require significant processing power to do the image processing required to obtain measurements at very high speeds. However, with the ever-increasing speed of digital signal processors and high-speed CMOS camera systems, this limitation is being constantly reduced [6][7][8][9][10].

III. GRID PATTERN DESIGN AND TRANSFER

In order to measure the absolute orientation or position of an object, there must be some frame of reference. For a vision-based measurement system, a frame of reference can be encoded onto the object to be measured as a specially designed pattern, and the camera system can then measure the movement of the object by analysis of the pattern. To use such a grid pattern, there must also be an efficient means of transferring it to the spherical body to be measured.

A. Grid Pattern Design

Several possible configurations could be considered for a pattern on a spherical surface. Perhaps the most natural and familiar is that of latitude and longitude lines like those found on a globe. Such a description is convenient because it is very similar to the definitions for spherical coordinates. Typical latitude and longitude line configurations consist of equally spaced lines. For absolute orientation determination, equally spaced lines present several problems. First, only incremental measurement is possible, and it is difficult to determine if lines have been missed. Such a system would also have some difficulty distinguishing similar configurations if it was unable to keep track of all previous information. The primary reason that equally spaced lines are especially ill suited for absolute orientation measurement is because it is impossible to determine the latitude or longitude angle that corresponds to a particular line which is a vital part of procedures commonly used for determining the absolute orientation of a spherical body. For this reason, there should be a means of identifying the latitude or longitude angle that corresponds to the grid pattern lines.

To solve the problem of associating a latitude or longitude angle with a particular grid line, the spacing between the grid lines has been chosen so that the absolute angle can be encoded by the nonuniform spacing of the grid lines. The spacing of the grid lines is chosen using a pseudo-random binary sequence in such a way that for some number of adjacent grid spacings, or word, there will be no repetitions throughout the entire grid line sequence. Therefore, it is possible to encode the absolute latitude or longitude angle via the spacing between the grid lines [11].

The spacing sequence, or absolute position string, is constructed based on the word length using a pseudo-random sequence. For a given word length, *m*, and a specified number of primitives, *p*, or allowed spacings, the number of unique words that can be created is p^m. The length of such an absolute position string is related to the number of unique words, and for a linear string with a beginning and ending point is $p^m + m - 1$. Figure 4 shows an example of a linear absolute position string. To encode a continuous 360° range of motion, a position string is required that does not have a beginning or end. This type of circular string has a length equal to the number of unique words, which is p^m. Special care must be taken when constructing a circular string to ensure that the entire string is valid. Figure 5 shows an example of a circular absolute position string.

In the absolute orientation sensing system, the latitude angles are encoded using a linear string because they cover only a finite extent, and the longitude angles are encoded with a circular string because they must cover the entire 360° range of motion. This grid pattern configuration can be seen on the spherical shell in Figure 6.

For p=2 and m=3
Number of unique words = p^m =n=8
Set of primitives = S ={0,1}

There are n unique words:

{0,0,0}	{1,0,0}
{0,0,1}	{1,0,1}
{0,1,0}	{1,1,0}
{0,1,1}	{1,1,1}

A linear string using all n words:

0 0 0 1 0 1 1 1 0 0

The overall length is p^m +m-1=10 elements.

Figure 4. Linear Absolute Position String Example

For p=2 and m=3
Number of unique words = p^m =n=8
Set of primitives = S ={0,1}

There are n unique words:

{0,0,0}	{1,0,0}
{0,0,1}	{1,0,1}
{0,1,0}	{1,1,0}
{0,1,1}	{1,1,1}

A circular string using all n words:

1 0 0
1 0
1 1
0

The overall length is p^m =8 elements.

Figure 5. Circular Absolute Position String Example

B. Grid Pattern Transfer

To use a grid pattern like that just described for absolute orientation measurement, there must be a means of transferring such a pattern onto a spherical body. Initial work done to transfer the grid pattern onto a spherical body used a specially designed three-degree-of-freedom actuator as shown in Figure 7. This actuator consists of a specially designed structure with three stepper motors, gimbal-like mount, and a cardan joint to allow the orientation of an object mounted on the actuator to be specified [11]. Figure 6 shows an image of the three-degree-of-freedom actuator with a spherical shell mounted on it. This apparatus was used to transfer the grid pattern to the spherical shell using a fine tip ink pen fixed in position in contact with the shell, and the shell was commanded to move in a specified trajectory in order to draw the desired grid pattern onto the shell. Taking great care in the operation of the spherical shell positioner apparatus, such an approach can be used to demonstrate the grid pattern concept. However, it would be unsuitable for mass production of such grid patterns. Other possible grid pattern transfer techniques that would be more suitable for mass production of such patterns are pad printing and block printing. In pad printing a compliant inkpad is used to transfer patterns onto objects with various shapes. Such an approach may be suitable for the grid pattern transfer application. Another possible approach would be to use a specially made three-dimensional printing block that contains the desired grid pattern to allow it to be stamped onto the spherical body.

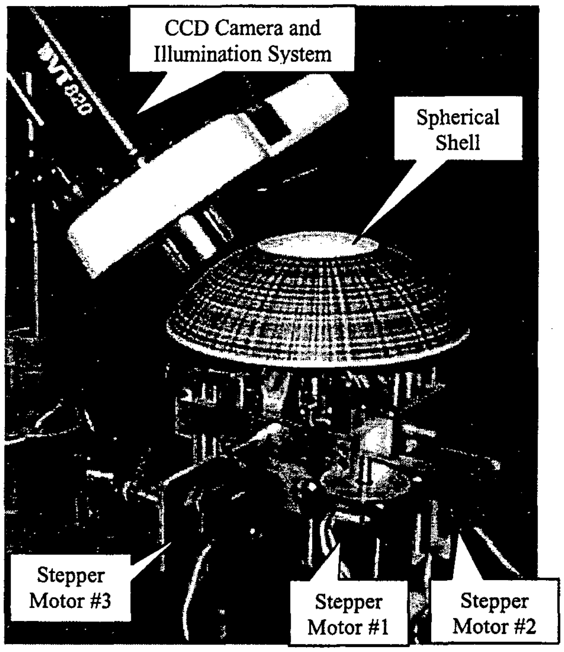

Figure 6. Spherical Shell Positioner for Grid Pattern Drawing

Figure 6 also shows a CCD camera and illumination system used to acquire images of the grid pattern. Figure 8 shows a typical image of the grid pattern on the spherical shell taken with a CCD camera. This pattern consists of a number of unequally spaced latitude and longitude lines on the surface of the sphere. The nonuniform spacings between the lines are chosen using the absolute position strings discussed previously. In this way, the absolute orientation information can be encoded into the grid pattern in a way that can be easily analyzed by a vision system, which will define a frame of reference on the spherical shell.

IV. GRID PATTERN IMAGE ANALYSIS

A very important aspect of the vision-based absolute orientation sensor is the image analysis of the grid pattern images. To obtain the absolute orientation information, the intersection points between the grid lines must be accurately determined, and the proper sequence of intersection points along a particular grid line must be know. An image analysis technique based on tracking along the grid lines has been developed, which has been found to give performance well-suited for real-time measurement applications compared with more conventional approaches such as the Hough transform [12][13].

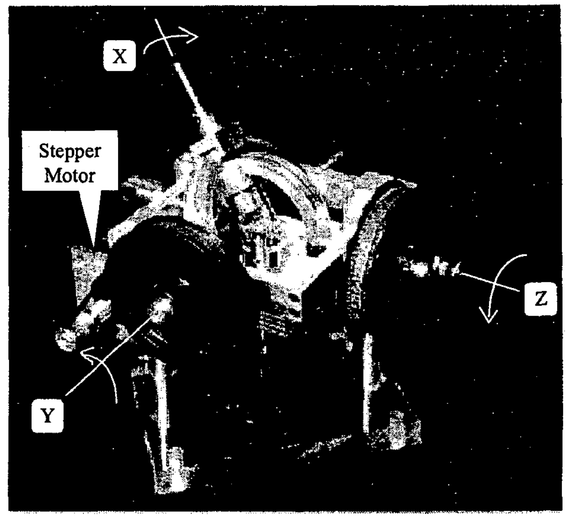

Figure 7. Image of Three-degree-of-freedom actuator

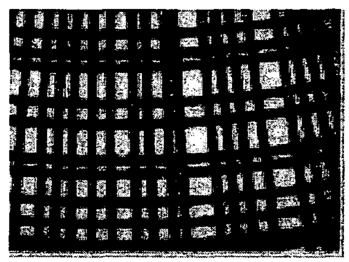

Figure 8. Grid Pattern Image

A box-shaped grid line-tracking algorithm is used to accurately determine the intersection points between the grid lines. Figure 9 shows an image with two perpendicular lines tracked, and the intersection points located. With these intersection points, the known spacing sequence from the absolute position string used to construct the grid pattern can be used to match the intersection points with the corresponding latitude and longitude angles.

With this information, the absolute coordinates of each of the intersection points can be easily found in a frame attached to the sphere using spherical coordinate definitions [13]. Using the results from a camera calibration procedure, it is possible to find the coordinates of these same intersection points with respect to a world coordinate frame fixed in space [14]. Figure 10 shows an image with as many intersection points as possible located. Using the absolute coordinates of these points on the spherical body, it is possible to use the grid pattern as a calibration object for automatic camera calibration. With these two sets of corresponding point sets in three dimensions, it is possible to use a closed-form absolute orientation procedure to find the absolute orientation between the sphere frame and the fixed world frame, which is the absolute orientation of the spherical body [15].

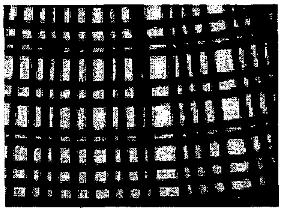

Figure 9. Image with 2 Perpendicular lines Tracked

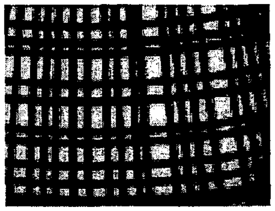

Figure 10. Image with All Lines Tracked

V. Application To Motion Control

In many types of control systems, delays associated with the measurement of some parameter of the system can play an important role in effective controller design. When using a vision-based measurement technique to obtain real-time measurements, the effects of the delay of the image processing system should be considered. A fundamental aspect of most vision-based measurement systems is the delay associated with the processing time required to obtain measurement information from an image. This effect leads to a delay closely related to the time required to process the image, and a quantization of the measurement values because new measurements are only available at some interval related to the processing time. Therefore, the measurement from the vision-based system is not simply delayed, but not actually available during the interval between measurements. This can also be considered as a dual-rate situation, because the sampling rate of the vision-based measurement system is less than the desired sampling rate of the controller.

To deal with the problems introduced by this dual-rate situation, special care must be taken in designing controllers to control the objects measured by such vision-based systems. Several approaches for dealing with the delay associated with the vision system are possible. Some approaches seek to estimate the system response between the slower sampled measurement signal to use for feedback control using model-based predictive techniques[16][17]. Adaptive control techniques to the dual-rate control problem have also been developed[18].

To investigate the effects of the difference in the rate of the orientation measurement and the desired control input rate, a dynamic simulation has been implemented in MATLAB the implements a single axis of the VR spherical motor system. This system with a simple delay is shown in Figure 11 where *I* represents one of the principle moments of inertia of the spherical rotor and τ is the delay in feedback path. This system also has a simple *PD* controller. It is important to note that this system does not exactly capture the dynamics of the dual-rate system because the measurement that is fed back is only available at certain discrete times and not simply delayed. However, this model is useful for controller design, and the MATLAB simulation does capture the true nature of the dual-rate nature of the system.

To investigate the performance of the system with the reduced rate measurement from the vision-based system, the step response was examined for several values of delay, which corresponds to the reduced sample rate of the vision-based measurement.

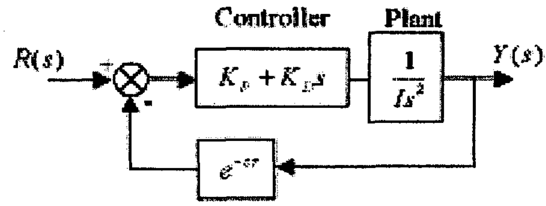

Figure 11. Block Diagram of Simple Delay System

Using a (2,2) Padé approximant for the delay, the root locus technique was used to design the *PD* controller [19]. Figure 12 shows the root locus of the system with the delay. The square blocks indicate the closed loop poles of the compensated system.

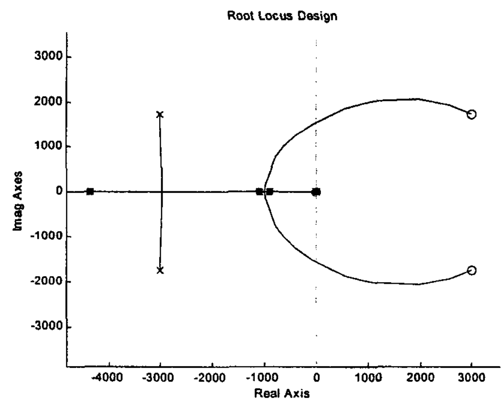

Figure 12. Root Locus of System with τ =1ms, K_D=0.22032, and K_P =2.2032

Figure 13 shows a plot of the 2% settling time of the step response as a function of the delay time. This plot shows an interesting trend with a minimum at 19ms. Such behavior would be very desirable for a vision-based system because for a real system the amount of time used to generate the measurement may have some variation. Therefore, if the minimum of the function in Figure 13 could be chosen near the nominal value of this measurement time, the performance of such a control system would be quite consistent.

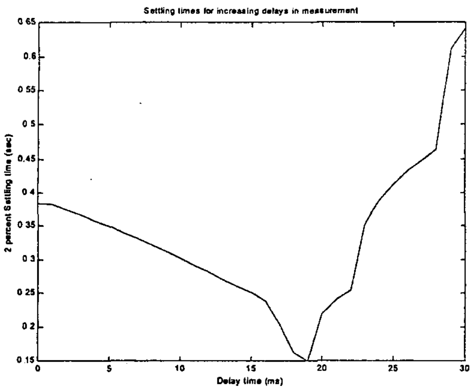

Figure 13. 2% Settling Time as Function of Delay

VI. Conclusions And Future Work

In this paper the development of a non-contact vision-based absolute orientation measurement system with application to the motion control of the VR spherical motor has been presented. The advantages of a vision-based measurement approach for making absolute measurements have been discussed. The design of a special grid pattern that allows the absolute orientation to be encoded onto a spherical object has also been presented. Techniques for transferring the grid pattern to a spherical object have been discussed. An image analysis approach based on tracking along the grid lines suitable for a real-time measurement system has also been reviewed. Finally, issues related to the use of such a vision-based measurement system in a motion control system have been presented with results from a dynamic simulation that incorporates the effects of the dual-rate aspects introduced by the relatively slower sampling rate of the vision-based system.

Future work will involve investigation of more efficient techniques for grid pattern transfer to a spherical body better suited for mass production of such patterns. Efforts will also be made to implement the image analysis algorithms on image processing hardware suitable for real-time vision-based measurement. Finally, additional techniques for compensating for the inherent delay present in the vision-based measurement system for motion control applications will be investigated.

Acknowledgement

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