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Ultra-Precision Angle Sensors and Multi-Axis Closed-Loop Control

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INTRODUCTION

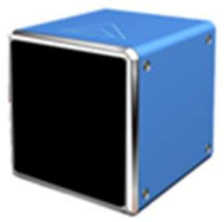
The concept of six degree-of-freedom closed-loop control for general positioning is often difficult to implement due to the lack of real-time independent measurements of position and orientation or at a cost that a broad application can tolerate. With real-time, ultra-precise and low-cost error measurements, a new class of multi-axis positioning systems can dynamically respond to changes in applied forces, wear, environment, etc.

We are proposing a new class of general positioning enabled by low-cost and ultra-precise angle measurement sensors that have been developed for commercial, industrial and military applications. These angle measurement sensors measure the angle between the sensor (or receiver / Rx) and remote targets (or transmitters / Tx) to arc-second precision. By measuring the angles to multiple Tx's or with multiple Rx's six degree-of-freedom position and orientation measurements can be made. The Rx's are composed of molded precision optical modules, specialized coding masks, analog optical detectors and digital processing. The Tx's are simple off-the-shelf LEDs or laser diodes, possibly including retro-reflectors. The actual precision of these sensors is essentially user-defined through signal strength or signal-to-noise-ratio or SNR. We call the general technology "Angle Coding" and the particular products Accu-Arc sensors.

Ultra-precise angular sensors can be used in a wide range of applications including:

- Navigation/localization of autonomous vehicles or handheld tools in controlled environments
- Localization of distant targets/tools relative to a fixed reference system
- Ultra-precise measurement/localization of distant objects via laser scanning
- High-speed, ultra-precise and low-cost closed-loop control of positioning systems. Angular positioning systems for example can be configured to reach angular precision of micro radians or tenths of arc seconds with kHz bandwidths.

Some characteristics of our Accu-Arc receivers are shown in Figure 1. The nominal Rx contains an optical module, analog and digital processing electronics and fits within a roughly 4.5 cm cube. The volume of the optics module is only about 1 cm^3 and so significantly more compact packaging is possible. The nominal angular precision can be about 4 arc seconds, depending on system SNR. The FOV is +/- 20 degrees. The nominal system update rate is 100 Hz although much higher speeds are possible. Targets (or Tx's) consist of 950nm modulated LEDs, laser diodes or reflected modulated light from laser scanning systems or retro-reflectors. Sixteen independent targets can be simultaneously measured.



Angular Precision	≥ 4 arc seconds (nominal)
Field of View	± 20 degrees
Update Rate	≤ 100 Hz
Number of Targets	≤ 16
Illumination Wavelength	950 nm

FIGURE 1: Nominal Accu-Arc receiver or Rx.

An example of measured angular precision is shown in Figure 2. The measurement was via a back-and-forth motion of +/- 180 arc seconds (or +/- 0.05 degrees) with a 100 Hz update rate. With a nominal configuration a particular Accu-Arc system can achieve an angular precision of about 4 arc seconds (20 μ radians) or better (depending on the SNR). With other configurations for applications requiring much higher precision, 0.1 arc second (0.5 μ radians) precision can be enabled.

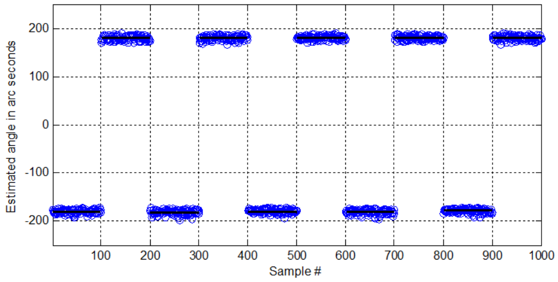


FIGURE 2: Example measured precision can be about 4 arc seconds (20 μ radians) for a nominal configuration with an update rate of 100 Hz. The black lines in Figure 2 represent the mean value of each section of estimates.

Angle Coding and Accu-Arc sensors are possible today because of a relatively recent convergence of ultra-precision optical array design, fabrication and assembly and advanced remote sensing theory and optimization. The Ascentia Imaging team pioneered many aspects of ultra-precision optical design, fabrication and assembly, including the development of wafer scale optics and cameras for the cell phone industry. The application of advanced radar techniques to what can be loosely called "cameras" was also pioneered by the Ascentia Imaging team, beginning in 1995.

SENSOR OPTICS AND DSP

Figures 3 and 4 describe the interior components of an Accu-Arc receiver. The major optical components from Figure 3 are the custom visible-block color filter, the 16 channel two-lens optical module, the light-absorbing lithographic intensity and optical NIR absorbing wedge masks and a 16-channel analog detector and trans-impedance amplifier board. Figure 4 shows the entire system assembled with the addition of an ADC board, processor board and I/O hardware.

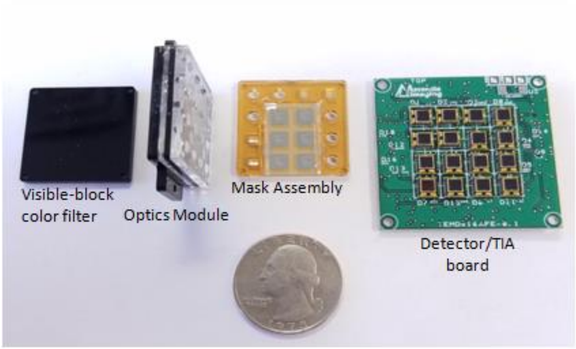


FIGURE 3: Optical assembly including analog single-pixel detectors.

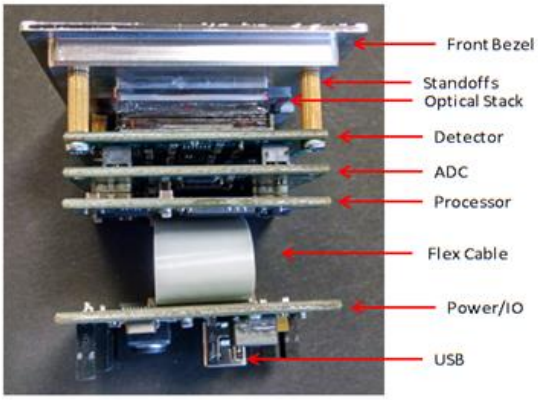


FIGURE 4: Optics with analog and digital electronics.

A summary of characteristics of the optical components include:

- Visible-block color filter: Custom dye formulation that acts as a high-pass optical color filter with cutoff at about 900nm. As the silicon detector has a steep cutoff at about 1000 nm, the combined color filter/detector has about a 100nm pass band.
- 16 channel optical module: 4x4 optical modules includes a first and second aspheric lens arrays and two spacers. Each optical channel is identical in the module and is designed so that the image of a point (or PSF) is a specialized form that acts with a lithographic intensity grating (as part of the mask assembly) positioned near the classical image plane to form sinusoidal intensity responses vs angle to a Tx. The aperture arrays, lens arrays, and spacers are all injection molded, and have molded self-aligning features that allow each component in each channel to be centered and spaced to better than 5μm relative to its

desired position. Both lens arrays and the color filter are AR coated.

- Mask assembly: Consists of a series of molded optical NIR optical absorbing “wedges” that act to form essentially linear intensity responses in NIR illumination vs angle to a Tx, and a series of NIR opaque lithographic gratings (seen as grey objects in the mask assembly in Figure 3). Since the alignment requirements for the lithographic gratings are even tighter than those for the other optical components, the gratings are actively aligned during the assembly process.
- 16 channel detector/TIA board: Single-pixel photon detectors, one for each of 16 optical channels, act to count the number of photons that are received through the optics after the intensity masks. Trans-impedance amplifiers, with gains of about 1M, act to maximize received SNR for weak Tx signals in the presence of strong interferers, like the sun, or at a maximum range. Negative DC feedback circuitry acts to prevent strong signals from circuitry bias or having the sun directly in the FOV of the Rx from saturating the ADC.

The unique nature of sensing angle-dependent intensity values enables sixteen orthogonal measurements that define a particular sensed angle. By comparing the measured values to calibration values, the measurements can then be used to estimate angle.

A conceptual view of the Accu-Arc Rx of Figure 4 is described in Figure 5. This view represents a slice through the 4x4 optical/digital structures. The completely custom analog optical front end consists of the visible-block color filter (CF), the lens arrays (L1 and L2), the spacer arrays (S1 and S2) and the mask assembly (Ma). The analog detector board (D/TIA) has a high-gain trans-impedance amplifier which prepares the analog signals for sampling. The digital section consists of off-the-shelf electrical components configured to convert the analog output from the D/TIA into digital form (A/D) and then process the resulting 16 channel digital stream into angle estimates.

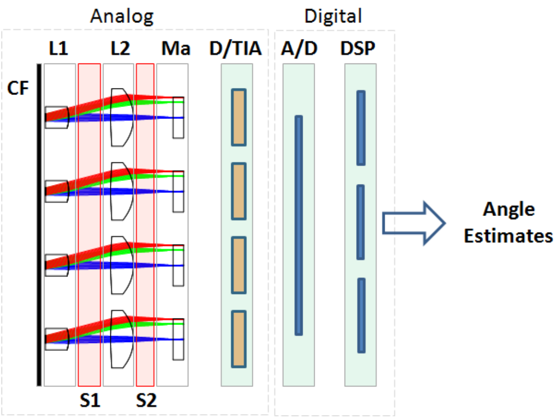


FIGURE 5: Layout of optical module and electronics.

The three sets of rays (colored blue, green and red) traced through the optics of Figure 5 represent the ray paths for three Tx’s positioned boresight to the sensor, 14 degrees to the sensor and 20 degrees to the sensor. The two-lens system is designed so that the rays intersect the mask assembly close to perpendicular and with a specially designed form (or PSF) so that the response measured at the output of the detector/ TIA is sinusoidal with angle.

Figure 6 shows example normalized intensity responses vs angle of three channels of the Accu-Arc system. The mask assembly acts to make the output of each optical channel unique and orthogonal to each other as a function of angle to a Tx. The signals from what we call low frequency (LF) channels vary essentially linearly with angle. The signals from what we call high frequency (HF) channels vary sinusoidally with angle. The HF signals are purposely designed so that pairs of resulting signals from different optical channels are shifted 90 degrees relative to each other. Because of the specialized optics, signals from the two high frequency channels closely follow a cosine and sine form. Or, pairs of high frequency channels are orthogonal to each other in Tx angle space. This is a fundamental characteristic of Accu-Arc systems that directly leads to ultra-precise angular estimation.

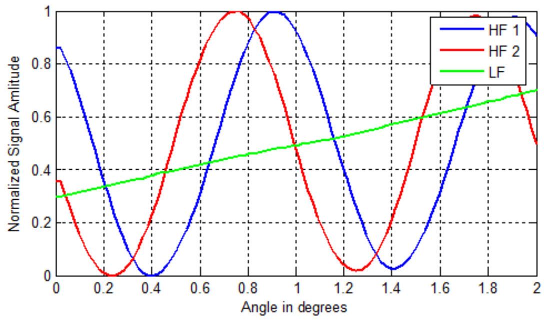


FIGURE 6: Normalized signals vs angular position on a Tx.

The HF channels in Figure 6 can be seen to have a much higher sensitivity vs angle than the LF channel. The HF channels in effect are responsible for high angular estimation precision, but with angular ambiguity. The LF channels are designed to un-wrap this angular ambiguity. The combination of LF and HF channels then enables high angular estimation precision over a wide FOV.

Another type of representation of the three curves of Figure 6 is shown in Figure 7. Instead of three 2D plots, Figure 7 shows the data plotted in 3 dimensions. Angle is now represented as position along a curve.

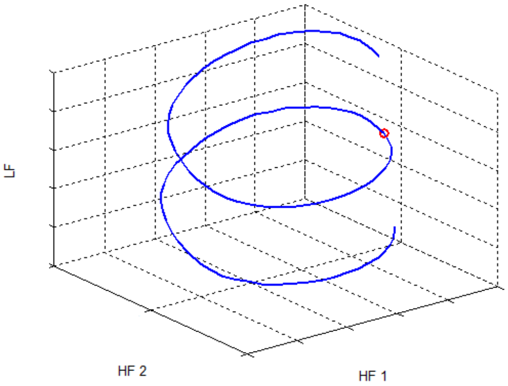


FIGURE 7: The curves of Figure 6 represented as a 3D plot.

Notice that the overall shape of this curve can generally be described as a “spiral” through 3 dimensions. There are two such spirals for 2D angular measurements. Any valid data from the 3 channels of Figure 6, over the same angular range, has to lie somewhere along this curve. The red circle of Figure 7, for example, represents the data of Figure 6 from the 1 degree point on the horizontal axis. Any invalid data, possibly due to reflections, dirt, dust, rain and snow, blocked apertures, other obstructions, etc. must lie significantly off this curve. This type of multi-channel configuration enables very fast and very precise digital detection and estimation.

MULTI-AXIS CLOSED-LOOP POSITIONING CONTROL

We are proposing that use of low-cost and precise angle sensors can enable a new class of close-loop control. In some cases, the main new aspect can be precision control with widespread affordability. Figure 8 describes a general layout of closed-loop positioning control.

With the actual position/orientation, a position/orientation error can be formed and the system commanded to reduce the error. With closed-loop control error reduction, or precision and accuracy, can then become an issue of degree-of-freedom position/orientation control and mechanical and electrical bandwidth rather than of positioning system mechanical stiffness.

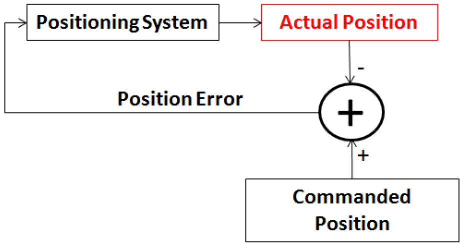


FIGURE 8: General layout of closed-loop position control. Actual position, with 6 degrees of freedom, can be available through Accu-Arc angle-measurement sensors.

Consider two rotation stages configured in a 2-axis gimbal positioning system, for a simple example (see Figure 9). This type of system can position an object via rotation in both the azimuth plane (or horizontal rotation) and elevation plane (or vertical rotation). Even if the single-degree of freedom of rotation is perfect for each stage, the actual precise 3D (or 6D) position/orientation of the mounted object is unknown and very likely far from that intended, if measured on a fine-enough scale. Even with open-loop calibration, the actual position/orientation is affected by mounting fixture(s) of the object, force and/or weight being applied to the stages, the speed and velocity of motion, environmental conditions etc.

How does even this simple 2-axis positioning system become more accurate, more precise and/or more affordable than commonly available today? Or, how can mechanical cost and complexity that translates into system stiffness be transferred to the relatively small cost and complexity of modern optics and electronics, while also increasing system performance? Modern Accu-Arc angle-measurement sensors offer one method of achieving next-generation precision positioning.

Figure 9 describes a conceptual and simplified 2-axis example gimbal system. This system has a fixture mounted near the 2D center of rotation. Mounted at a distance d from the center of rotation are two or more sets of LEDs or retroreflectors. Remote Accu-Arc angle-measurement sensors are mounted a distance R from the LEDs. The sets of LEDs enable 6DOF position and orientation estimates from the Rx's.

The sensors form a metrology frame that can be used to close the loop on the position of the axes relative to that metrology frame, significantly increasing the accuracy of positioning and orientation [1]. Because the metrology frame is stiff and provides a reference for the directly measured positions of the axes, the axes themselves do not require precise calibration, and do not require extreme stiffness to maintain that calibration. What can the measured angular precision of the object be with such a system layout?

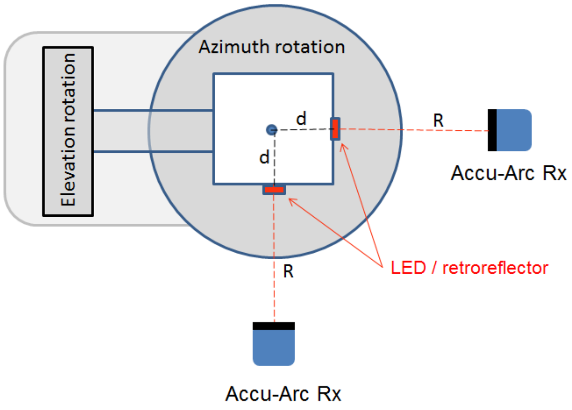


FIGURE 9: Example 2-axis gimbal positioning system.

Estimation theory and the Cramer-Rao Bound / Fisher Information [2] allows an understanding of the potential precision available to the commanded positioning of the rotational axes of Figure 9. These are the same theoretical estimation tools that are used to design Angle Coding systems.

If the standard deviation of the Accu-Arc Rx's angular measurements is $\sigma_{\text{Accu-Arc}}$, then the measured standard deviation of the commanded angle can be:

$$\sigma_{\text{axes}} \leq \frac{R}{d} \text{ x } \sigma_{\text{Accu-Arc}}$$

Or, the angular measurement precision of the axes of the system of Figure 9 can be linearly related to the angular precision of the Accu-Arc Rx's that are remotely measuring the angle to the LEDs or retroreflectors. The potential angular extent of the positioning axes of Figure 9 is (R/d) times the FOV of the Accu-Arc Rx. System design then entails the balancing of the physical dimensions (R/d), the update rate (Hz to khz), and geometry to suit the application. The nominal FOV, from Figure 1, is about +/- 20 degrees. Use of multiple Rx's can increase the FOV and thus angular extent.

There are a large number of possible configurations for even two-axis gimbal systems, often application-specific configurations, beyond that of Figure 9. LEDs/retroreflectors can be distributed throughout the system for ease of use as well as accurate position / alignment / orientation measurement. More than two Rx's can be used to enable larger motion of the stages along with compact form factors of the entire system. As the distance R for compact systems can be 1m or less, standard LED's and/or retroreflectors with laser diode sources can enable a broad range of SNR's and therefore very high potential precision for the novel Accu-Arc configurations. Variations in Accu-Arc Rx's such as simultaneous sampling of different Rx's and kHz update rates are possible.

CONCLUSIONS

Multi-axis closed-loop control with low-cost precision sensing has the potential to increase the performance and affordability of future positioning systems. With remote real-time position and orientation measurements the entire control system can be centered on mechanical and electrical bandwidth and less on classical calibrated open-loop control that relies on static calibration and stiffness in independent axes. Accu-Arc angle measurement sensors can possibly enable such future systems.

REFERENCES

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[2] Louis L. Scharf, Cédric Demeure. Statistical Signal Processing: Detection, Estimation, and Time Series Analysis. Addison-Wesley Publishing Company. New York: 1991