System-on-a-chip based nano star tracker and its real-time image processing approach

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ABSTRACT

The star tracker is one of the most accurate components for satellite attitude determination. With the development of the nano star tracker, it is compatible for application on small satellites. However, the drawback in dynamic property of nano star tracker has limited its extensive applications. The principal objective of this study is to introduce a system-on-a-chip (SOC) based nano star tracker with enhanced dynamic property. A morphology based image processing approach was realized based on single FPGA to achieve real-time star extraction, even from a blurred image. Such nano star tracker has been developed and tested, and field experiment results indicated that its dynamic range was up to 4°/s with a data update rate of 30Hz. Moreover, the orientation of the satellite with developed nano star tracker on board has been analyzed based on the telemetry data. Thus, such nano star tracker could promote its applications on small or agile satellites.

INTRODUCTION

Nowadays, the advantage of small satellites have intrigued rapid development of new technologies or products [1]. Due to the small size and low weight, it is promising to utilize small satellites for remote sensing or optical application where agility control is required. Although star trackers are the most accurate attitude determination sensors, traditional star trackers have the disadvantage of large size, heavy weight, high power consumption and poor dynamic characteristics [2, 3].

Fig. 1 shows three different kinds of star trackers developed by Tsinghua University. The micro star tracker is a traditional star tracker, which has been proven successful for high accuracy with several times of in-flight experience [4]. The electrical structure of micro star tracker is based on FPGA and DSP; FPGA is employed for image capturing and DSP is employed for image processing. In such structure and image processing procedures, a whole image should be stored in SRAM for image processing, resulting in large storage memory. Furthermore, image capturing and image processing are separated, and image processing cannot be executed until a whole image is fully acquired and stored in memory, which leads to a low data update rate (5Hz, as listed in Table 1).

In this study, a System-on-a-Chip (SOC) based nano star tracker was developed with 50 × 50 × 100mm³ in size and 245g in weight. To make full use of such SOC based structure, a morphology based image processing approach was implemented by hardware and the data update rate was improved to 30Hz. Field test results indicated that the proposed image method was robust in...
high dynamic conditions and the dynamic range of the nano star tracker was up to 4°/s.

**HARDWARE DESIGN OF SOC BASED NANO STAR TRACKER**

To realize application on small satellites, especially on nano or pico satellites, two different kinds of novel star trackers have been developed in Tsinghua University, as shown in Fig. 1(b) and Fig. 1(c). Their main properties are listed in Table 2. With a 12°×15° field of view, the pointing accuracy of nano star tracker is better than 7°(3σ) and its rolling accuracy is better than 70°(3σ), which is comparable with the high accuracy of traditional star trackers; while the nano star tracker is approximately ten times less in size and five times less in weight. Also, the pico star tracker is further smaller and lighter with the same high accuracy.

**Table 2: Properties of nano/pico star tracker**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nano Star Tracker</th>
<th>Pico Star Tracker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>7.0°, 70°(3σ)</td>
<td>7.0°, 70°(3σ)</td>
</tr>
<tr>
<td>Size</td>
<td>50×50×100mm³</td>
<td>32×32×45mm³</td>
</tr>
<tr>
<td>Mass</td>
<td>245g</td>
<td>50g</td>
</tr>
<tr>
<td>Power consumption</td>
<td>0.7W</td>
<td>&lt;0.5W</td>
</tr>
<tr>
<td>Slew rate</td>
<td>2°/s</td>
<td>1°/s</td>
</tr>
<tr>
<td>Data update rate</td>
<td>10Hz (Optional)</td>
<td>5Hz</td>
</tr>
</tbody>
</table>

A single SOC structure design could reduce unnecessary power consumption with comparison to the conventional FPGA and DSP structure. The function of the SOC chip is illustrated in Fig. 2. The core function of SOC is the hardware implementation of image processing method, which will be discussed in the next section. Besides, there is an embedded microprocessor, which operates the communication with OBC and attitude calculation algorithm. The star info registers will be updated with information of new extracted stars for attitude calculation; and quaternion registers will be updated with information of new quaternions. Since all these registers could be accessed by both hardware image processing module and the embedded microprocessor, a double-check mechanism was introduced to get rid of the sudden update during register read. The attitude calculation module was designed to fulfill both the capture mode (lost in space mode, with no acknowledged attitude information) and the tracking mode (with previous attitude information). Moreover, for the purpose of in-flight image acquirement, snapshot is optional in such system with an extra SRAM, which could be accessible through FPGA interface. The data of a whole image could be extracted from telemetry data according to the protocol. With such structure, the power consumption of the nano star tracker is significantly reduced to 0.7W, which is half of the power consumption of traditional star trackers.

![Figure 2: Flow chart and schematic structure of the SOC](image)
IMPLEMENTATION OF THE IMAGE PROCESSING METHOD

In this study, a morphology based image processing method is introduced with pipeline structure and local background analysis. By employing such structure, the image processing can be done during the image capturing, meaning that background analysis, image filtering, as well as image explosion and pixel read out could be parallel processing. Such pipeline structure is illustrated in Fig. 3 and theoretically, it introduces no time delay and no storage memory is required. After exposure of a whole line of pixels, the readout of gray value of the pixels in current line begins at moment $T_1$ and ends at moment $T_2$. During the line image readout, the line image processing starts at moment $T_3$ and ends at moment $T_4$. The delay between $T_1$ and $T_3$ is solely determined by the structuring element utilized in the morphology operations (erosion and dilation [5]). The main image processing includes background analysis, image de-noise and star extraction. The position of all extracted stars will update at the end of a whole image.

Figure 3: Schematic of real-time image processing method

The implementation of such morphology image processing method was based on the SOC hardware structure. As detailed in Fig. 4, the solid circles represent the variables during the processing and the solid rectangles represent the operations, including morphology operations and other logic operations. There are two main parts in this chart divided by a red dash line. Below the dash line, the image is de-noised to realize local background analysis and above the dash line, the image is further filtered to realize star extraction and star position determination.
For each operation in Fig. 4, it could be abstracted as an operation box with input ports and output ports, as shown in Fig. 5. The ports of a basic module were listed in Table 3. For example, if such basic module is used to realize the function of an erosion operation, the input signal of Din_valid port should be the line valid signal and the frame valid signal from the CMOS image sensor and the input signal of Din_data port should be the gray value of the corresponding pixels. With the built-in structuring element in the module, the valid signal of the Dout_data could be output after several cycles of the module clock.

Timing simulation has been carried out to examine the hardware function. Fig. 6 indicated the time delay simulation results and the total delay for a whole image with 1024 lines of pixels is the readout time for 3 lines, which is 0.29% of the whole image readout time. Such real-time image processing approach can be implemented to achieve a 30 Hz or above data update rate.

**Figure 4: Hardware flow chart of morphology based image processing approach**

**Table 3: Ports of a basic module**

<table>
<thead>
<tr>
<th>Port name</th>
<th>Signal direction</th>
<th>Signal function</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLK</td>
<td>Input</td>
<td>Module clock</td>
</tr>
<tr>
<td>RST</td>
<td>Input</td>
<td>Module reset</td>
</tr>
<tr>
<td>Din_valid</td>
<td>Input</td>
<td>Valid data indicator for timing control</td>
</tr>
<tr>
<td>Din_data</td>
<td>Input</td>
<td>Image data input</td>
</tr>
<tr>
<td>Dout_data</td>
<td>Output</td>
<td>Image data output after processing</td>
</tr>
</tbody>
</table>

**Figure 5: Basic module for hardware implementation of image processing method**
EXPERIMENTS AND DISCUSSIONS

Dynamic test and results

Dynamic performance of the nano star tracker was examined by employing a rotary table at field experiment. The prototype of the nano star tracker was fixed onto the rotary table, as shown in Fig. 7, initially with its principal axis (+Z) pointing to the zenith and other two axes pointing to the geographically east (+X) and north (+Y), respectively. The starting position of each test cycle was achieved by rotating the prototype by 5° around −X axis from aforementioned initial position.

During the sky night experiment for dynamic property, the rotation rate of the rotary table could be well controlled by the console and the maximum rotation rate is set to 4°/s in this study. Firstly, the prototype was rotated by 10° around +X axis with its principal axis passing through the zenith for 5°. Then, a reversed rotation was carried out after a short pause, ensuring that the ending position was the same with the starting position. A whole test cycle was constituted by such two rotation stages, shown as stage ① and stage ② in Fig. 8. At each specific rotation rate, two test cycles were conducted to collect the output of the nano star tracker prototype. When the rotary table is stationary, the quaternions would remain unchanged for that transient time; while during each rotation stage (①, ②, ③, and ④), the quaternions would vary with the change of the current pointing direction. Furthermore, the tendency of the variation or the slope of each quaternion at dynamic condition is in compliance with the direction of the rotation and two counter stages resulted in opposite variation tendency of quaternions.

The image data was acquired during dynamic test as well. Based on the image distribution of a specific star at different rotation rate, as shown in Fig. 9, the energy concentration of the star image is still qualified for successful extraction, even at a high dynamic condition.
Preliminary orientation analysis based on telemetry data

The nano star tracker has been on board a nano-satellite NS-2, which is a three-axis stabilization nano satellite for more than nine months and it have been functioning well for both attitude determination and angular rate estimation [6].

Besides, the orientation of the satellite with respect to the sun and the earth could be preliminarily analyzed through the telemetry data. As shown in Fig. 10, the background gray value of a whole image was extracted from the telemetry data. The background gray value varied periodically: when it reached the saturation value (255), the attitude information is invalid, indicating that the sun or the earth was inside the FOV of the nano star tracker; while on the other hand, the attitude information in valid with a low background gray value, indicating that the sun or the earth was outside the FOV of the nano star tracker. During the valid attitude period, the average number of identified star was 10~20, approximately.
According to the time stamp of the analyzed telemetry data, the sun vector at that time was calculated to be (-0.915, -0.374, -0.150). The angle between the sunlight and the principal axis of the nano star tracker could be determined during the valid attitude period, as shown in Fig. 11. The calculated angle was greater than 90°, indicating that the sunlight did not enter the FOV of the nano star tracker and the invalid attitude was caused due to the earth appearance within the FOV of the nano star tracker.

Figure 11: The angle between the principal axis of nano star tracker and the sunlight

CONCLUSION

In this work, we introduced an SOC based nano star tracker, whose average power consumption is 0.7W due to SOC based electrical design. A real-time image processing approach was implemented to further improve the dynamic performance of the nano star tracker. By employing such structure and morphology-based image processing algorithm, the image processing including background analysis, image de-noise and star extraction could be conducted in parallel with image capturing. This approach introduced almost no time delay for star centroid determination and there would be no memory space required for image storage as well. The nano star tracker functioned well when it was fixed to a rotary table and rotated at the angular rate up to 4°/s. Moreover, it has been launched into space onboard a nano-satellite NS-2 for 9 months and according to the telemetry data, the attitude, the angular rate and the orientation of the NS-2 were successfully determined. Therefore, such nano star tracker could improve the performance of small satellites, especially for application on remote sensing, or agile small satellites with large angle maneuver.

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